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Improved Stench Fire Warning for Underground Mines

By William H. Pomroy and Terry L. Muldoon

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNITED STATES DEPARTMENT OF THE INTERIOR
Donald Paul Hodel, Secretary

BUREAU OF MINES
Robert C. Horton, Director

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

atm	atmosphere, standard	μm	micrometer
°F	degree Fahrenheit	pct	percent
ft	foot	ppb	part per billion
ft^3	cubic foot	ppm	part per million
ft^3/min	cubic foot per minute	psi	pound per square inch
h	hour	psia	pound per square inch, absolute
in	inch	psig	pound per square inch, gauge
lb	pound	s	second
lb/MMft^3	pound per million cubic foot	wt pct	weight percent
mg/kg	milligram per kilogram	yr	year
mi	mile		
min	minute		

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IMPROVED STENCH FIRE WARNING FOR UNDERGROUND MINES

By William H. Pomroy[1] and Terry L. Muldoon[2]

ABSTRACT

This report describes Bureau of Mines research that led to the design, prototype fabrication, and successful proof-of-concept testing of an improved stench fire-warning system for underground noncoal mines.

Stench systems are the most widely used means of warning miners in underground noncoal mines of fires or other emergencies. A stench system alerts miners that an emergency condition exists by injecting an odorant into the mine air. Although stench warning systems have been used successfully for over 60 yr, present systems suffer several serious shortcomings, including odorant toxicity, unreliability of warnings, widely varying stench concentrations, and others.

In 1980, the Bureau began a research program to upgrade the stench warning system. The resultant system overcomes the deficiencies of existing systems by substituting tetrahydrothiophene for the commonly used ethyl mercaptan stench odorant, and through the use of a specially designed stench injector. The improved injector reliably meters stench fluid into either ventilation-air or compressed-air streams at a precisely controlled rate. Prototype hardware has been fabricated and proof-of-concept tested under both laboratory and in-mine conditions.

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INTRODUCTION

Fires in underground noncoal mines are a serious hazard to life and property. From 1965 to 1979, there were 115 reportable fires (at least 30 min in duration or resulting in injury) in U.S. underground noncoal mines, accounting for 119 fatalities (1).[3] Countless millions of dollars were spent on rescue and recovery efforts, equipment repair and replacement, and mine rehabilitation. In addition, mines shut down by fires were forced to forego hundreds of millions of tons of mineral production.

[3]Underlined numbers in parentheses refer to items in the list of references at the end of this report.

The primary safety hazard in an underground fire is contaminated air. Since the mine's limited fresh-air supply can be rapidly consumed and replaced by smoke and toxic gas, the mine must be evacuated as quickly as possible in the event of fire. However, mine evacuation is often a very time-consuming process.

In a recent survey of 50 underground noncoal mines, emergency evacuation times ranged from 5 to 85 min, with a strong correlation between the time required for evacuation and the maximum depth of the main shaft (fig. 1) (2). Compounding the problem of longer evacuation times for deeper mines is the fact that work forces in deeper mines are usually larger than

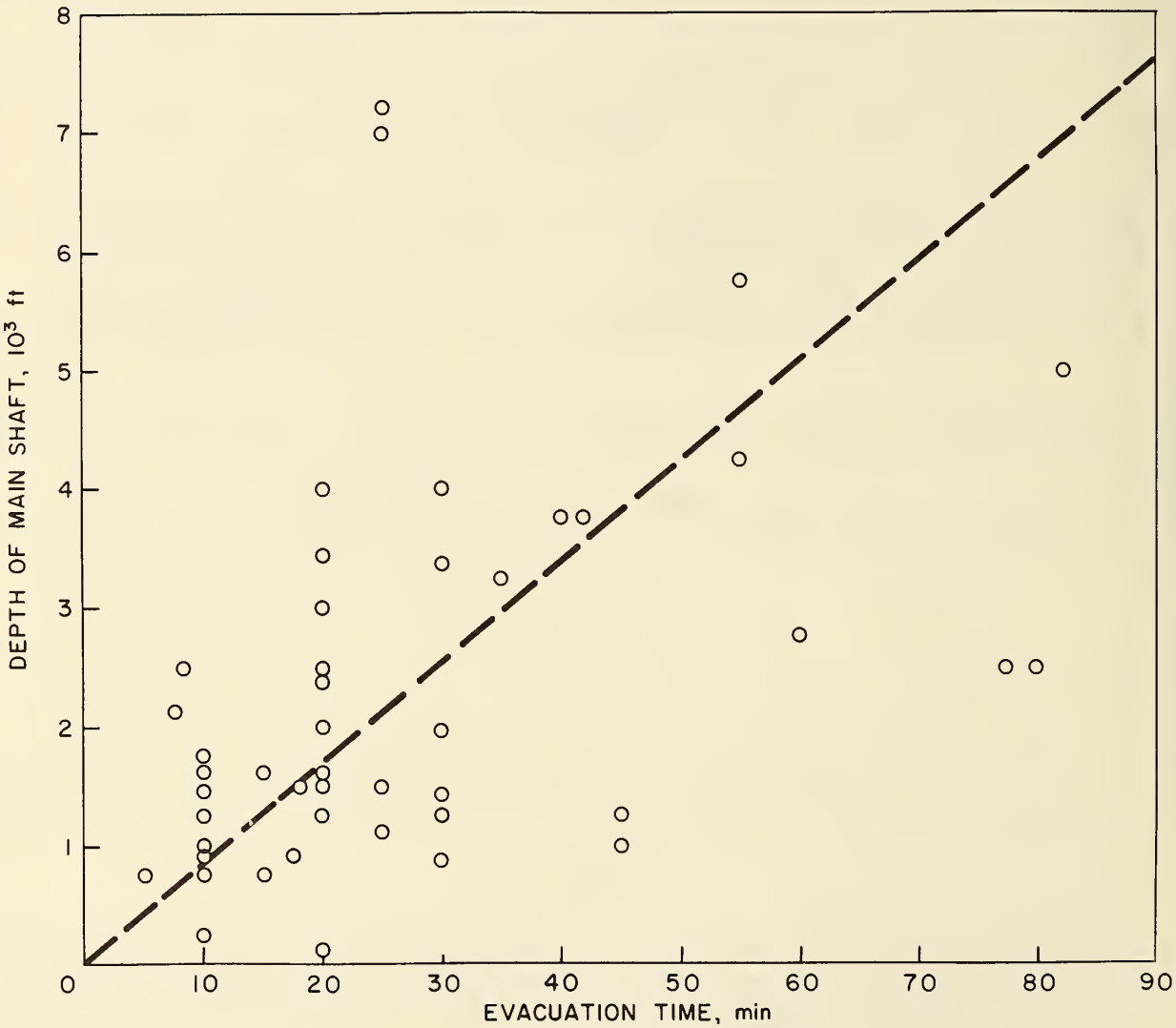

FIGURE 1. - Evacuation time versus maximum depth of main shaft.

work forces in shallower mines (fig. 2). The average work force in mines between 3,600 and 7,700 ft deep is 195 miners per shift, whereas the average work force for mines less than 1,800 ft deep is only 84 miners per shift. As mines become deeper with the depletion of shallower ore bodies, these problems of long evacuation times and more miner exposure to fire hazards will tend to get worse.

Mine fire evacuation must begin as soon as possible after a fire has been detected. The miners must be warned, and they must then follow an emergency escape preplan. Since time is of the essence, detection, warning, and escape must all be accomplished as reliably and quickly as possible. However, fire-warning technology, the essential link between detection and evacuation, has not kept pace with advances in detection and evacuation planning.

In a typical stench system, ethyl mercaptan, a highly odoriferous organic compound, is released from the surface into the compressed-air and/or ventilation-air streams of the mine. The liquid is quickly vaporized, and the stench is carried in the airstreams to the working areas underground. Miners, upon smelling the stench, evacuate the mine according to the emergency preplan.

Although the stench system has been used successfully for over 60 yr, it suffers several serious shortcomings owing to certain chemical properties of ethyl mercaptan and certain performance characteristics and limitations of present injection systems. These shortcomings include (1) toxicity of the odorant which can lead to debility in miners; (2) reactivity of the odorant with iron oxide, which can result in unreliable warnings because the odor may fade when transported long distances in steel pipe; (3) lack of control over the rate of agent release into the airstream, with the result that some work areas may receive unbearably high stench concentrations while other areas are missed

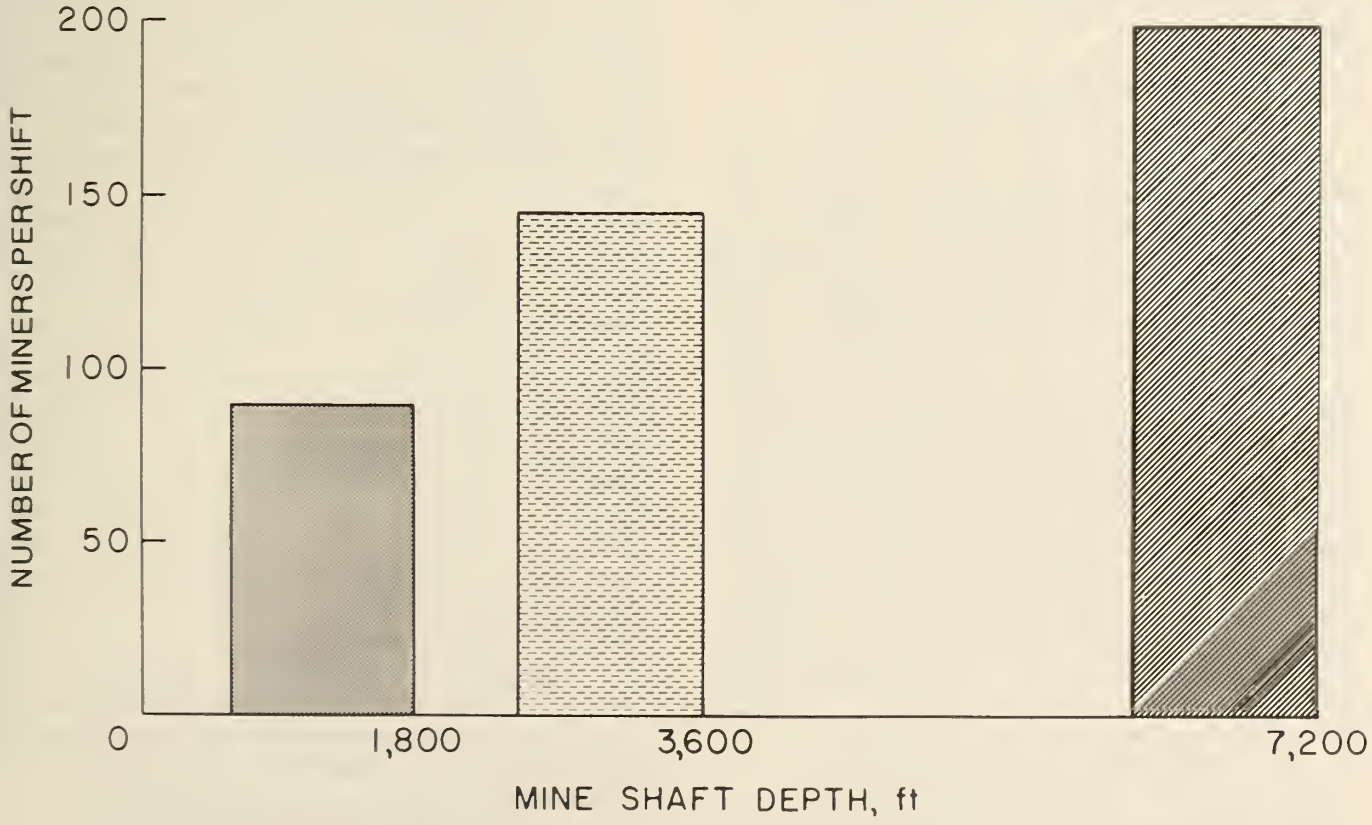

FIGURE 2. - Size of underground workforce versus depth of mine.

altogether; (4) lack of visual indications of system status, valve positions, and proper system operation; and (5) excessively long stench transit times.

In 1980, the Bureau of Mines embarked on a research program to upgrade the stench warning system. The objectives of this program were to improve the safety, reliability, and effectiveness of stench systems. The work done under this program was accomplished through a research and development contract with Foster-Miller Associates, Inc., Waltham, MA (3-4), and is described in detail in this report.

ALTERNATIVES TO STENCH WARNING

Although the primary thrust of the research program was to upgrade the stench system, the following sections are included to acquaint the reader with available and near state-of-the-art mine warning system options. Subsequent analyses of existing stench warning technology and the improved stench warning system developed by the Bureau are more meaningful when considered in the context of mine warning systems in general.

Two alternatives to stench systems are now used on a limited basis: electrical and messenger systems. Radio systems, although not in current use, are often mentioned as a possible successor to the stench system.

ELECTRICAL SYSTEMS

Electrical warning systems are used where compressed-air equipment is not used extensively and where ventilation velocities are low. Bells, flashing lights, gongs, and horns have been tried and have achieved limited success. However, these systems are not effective when miners are working outside the visible or audible range of the alarm or when mine power fails. Where electrical equipment is used extensively in the mining operation, interruption of the power supply has sometimes been used to signal an emergency. However, this system is also unreliable because power interruptions are common in many mines, and electrical equipment may not be in use when an emergency occurs.

MESSENGER SYSTEMS

A messenger system depends on the miners to physically communicate the emergency warning from person to person. Some mines use a messenger system as the primary warning system, but more commonly a messenger system is used as a backup to the primary system. Messenger systems are particularly common in small mines where personnel are not spread out over a large area and/or where telephone systems are both reliable and extensive. The chief disadvantage of the messenger system is the time required for the signal to be passed to each worker.

RADIO SYSTEMS

Prototypes of high frequency (HF), very high frequency (VHF), and ultrahigh frequency (UHF) leaky-feeder wireless radio-transmission communication systems have been constructed and tested in several noncoal underground mines. Although originally designed for the geometry of coal mines, it was hoped these systems would find application in noncoal mines as well. However, test results showed signal ranges were limited to 30 to 50 ft from the transmission cable (5).

An alternative to the leaky-feeder approach is provided by medium frequency (MF) transmission. MF has the unique capability to couple into, and reradiate from, continuous conductors in the mine (rails, trolley lines, water pipes, air lines, phone lines, etc.) in such a way that these conductors become not only the transmission lines, but also the antenna system for the signals (6).

Although this parasitic coupling effect provides greater signal-transmission coverage, in comparison with leaky-feeder systems, MF systems have problems in reliably receiving the transmitted signal. Large, protruding antennas are required on vehicular transceivers, and users of personal transceivers must wear

a specially designed vest containing an antenna and radio-circuit modules. In addition, total mine coverage is not assured due to limits on signal range and through-the-rock transmission. Miners in remote stopes and development headings that are not linked to the rest of the mine by continuous conductors are most vulnerable, yet typically they are faced with the longest evacuation times.

DEFICIENCIES OF EXISTING STENCH WARNING SYSTEMS

The air-carried-stench system is the most popular means of emergency warning in noncoal mines because it is the most practical, versatile, and effective means currently available. Despite several serious shortcomings, its use and acceptance is widespread because the alternatives offer lower levels of safety and reliability. Stench system deficiencies addressed through this research include the following:

1. Ethyl mercaptan is highly reactive with iron oxide (fig. 3). Therefore, the odor tends to fade when it is transported in steel pipe. (For this reason, ethyl mercaptan is no longer used as an odorant in the natural gas industry.)

2. Ethyl mercaptan is highly toxic. The 8-h time-weighted average concentration limit (threshold limit value, or TLV) established by the National Institute for Occupational Safety and Health (NIOSH) and the American Conference of Governmental and Industrial Hygienists (ACGIH) is 0.5 ppm. As a comparison, the NIOSH TLV for hydrogen cyanide is also 0.5 ppm. An absolute limit of 2 ppm has been set by ACGIH for exposures of 15 min or less. In low concentrations, ethyl mercaptan can cause headaches and nausea. At higher levels, it can irritate the skin and eyes, affect liver function, affect amino acid levels in the blood, and retard redox processes.

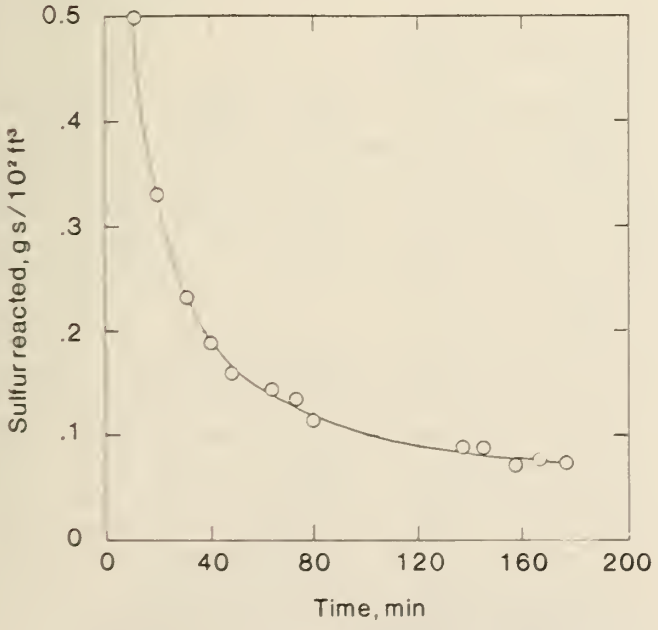

FIGURE 3. - Reactivity of ethyl mercaptan with iron oxide.

3. The odor intensity of ethyl mercaptan tends to increase steadily with increasing stench concentration. When personnel are exposed to high concentrations of stench, the odor can be overwhelming.

4. Ethyl mercaptan is highly corrosive to injection equipment and air lines. Prolonged use of ethyl mercaptan can damage injectors to the extent that proper function may be impaired.

5. The injection methods release the stench in a totally uncontrolled fashion. As a result, areas of the mine near the injection point may be overwhelmed by the stench odor, and miners in those areas are likely to be exposed to potentially toxic concentrations of ethyl mercaptan.

6. The injection methods have been unreliable. Injection equipment is often "homemade" and "free lanced." "Designs" are often strongly influenced by the availability of miscellaneous parts at the mine site.

Typical problems include operating procedures that are complex and therefore improperly followed, frozen valves, mismatches in size and shape between major system components and stench-fluid refill containers, and unsatisfactory and/or incompatable materials of construction.

7. Available injection equipment does not permit visual system status checks. An empty or nonfunctional injector is not readily apparent, and if unnoticed until needed during an actual emergency, precious time could be lost while refilling it or performing repairs.

8. Current systems do not have visual indications of valve positions. It is difficult for personnel to know if valves are completely open or completely closed, especially when valves are frozen or sluggish.

9. Available systems have no immediate visual indications of proper system operation. The only positive confirmation that the odorant has been released is to contact personnel underground, and this is often a time-consuming process.

10. Current systems seldom achieve total mine coverage. Remote workplaces, workplaces not using air equipment, and dead-end headings are often missed.

11. Stench transport times can be unacceptably long.

In addition, certain functional deficiencies in the stench system are inherent due to its reliance on moving airstreams to carry the warning signal. The heat-induced buoyancy effects of a mine fire, for example, may cause throttling or reversals of ventilation flows. Stench injected into intake air may be exhausted if the intake air flow is reversed. Areas with poor or slow ventilation and/or areas distant from compressed-air equipment may not receive the stench warning signal. It was beyond the scope of this research to treat such inherent limitations. However, as mines become deeper, as workings become more complex, and as diesel and electric equipment displace compressed-air equipment, the need for novel warning systems that will address these problems will grow.

DEVELOPMENT OF IMPROVED STENCH SYSTEM

The development of an improved stench system capable of safely, effectively and reliably warning underground personnel of an emergency was accomplished in two steps: First, a stench agent was selected; and second, an improved injector was developed.

SELECTION OF STENCH AGENT

A survey of industrial gas odorizing agents was undertaken to identify a suitable substitute for ethyl mercaptan. Many compounds were surveyed, and five were selected for detailed evaluation: isopropyl mercaptan, amyl acetate (banana oil), dimethyl sulfide, tertiary butyl mercaptan, and tetrahydrothiophene (THT). Factors considered were boiling point, freezing point, vapor pressure, flashpoint, flammability limits, reactivity, solubility in water, toxicity, odor threshold, availability, cost, and past industrial uses. The results of the final evaluations are summarized in table 1.

THT emerged as the most desirable agent for use in the stench system. THT is widely used in Europe as a natural gas odorant and has been used successfully on a limited basis in this country for the same application. THT is not reactive with iron oxide, so it is not subject to "odor fade." The odor intensity of THT tends to stabilize at a moderate, easily recognizable level, and it is much less corrosive than ethyl mercaptan.

TABLE 1. - Properties of industrial gas odorants evaluated against ethyl mercaptan[1]

	Ethyl mercaptan (C_2H_6S)	Tetrahydrothiophene (C_4H_8S)	Amyl acetate [$(CH_3CO_2CCH_2)_4CH_5$]	Dimethyl sulfide (C_2H_6S)	Isopropyl mercaptan (C_3H_8S)	Tertiary butyl mercaptan ($C_4H_{10}S$)
Synonyms	Ethanethiol, EtSH	THT	Pentylester, banana oil, pear oil.	Methyl sulfide	2-propanethiol	t-butanethiol, TBM.
Molecular weight	62.13	88.18	130.21	62.13	76.17	90.20.
Physical properties:						
Specific gravity	0.841 at 60° F	1.002 at 60° F	0.876 at 68° F	0.85 at 60° F	0.817 at 60° F	0.830 at 68° F.
Vapor density (value given times density of air).	2.14	3.04	4.5	2.14	NA	NA.
Boiling point at 1 atm, °F	100	~212	300	38	NA	~194.
Freezing point, °F	-148	-50	NA	-98	NA	34.
Vapor pressure at 100° F, psia	16.3	0.7	0.817	14.9	8.8	~6.8.
Flashpoint, °F	1°	55	~104	-34	0	10.
Flammability:						
Lower limit, pct	2.8	NA	1.97	2.2	NA	NA.
Upper limit, pct	18.2	NA	NA	20	NA	NA.
Classification	Extremely flammable	Flammable	Flammable	Extremely flammable	Extremely flammable	NA.
Chemical properties:[2]						
Reactivity	Oxidizes readily in presence of iron oxides.	Nonreactive	Nonreactive	Nonreactive	May oxidize in presence of iron oxides.	May oxidize in presence of iron oxides.
Solubility in H_2O, wt pct	0.7 at 68° F	Negligible	Slightly soluble	2 at 68° F	Slightly soluble	0.3 at 68° F.
Toxicity data:						
8-h TWA conc limit, ppm	0.5	Not established	100-125	Not established	Not established	0.5.
LD_{50}, oral, for rats, mg/kg	1,960	2,450	6,500	535	2,000-5,000	1,500.
LC_{50}, inhalation, for rats, ppm	4,420	44,200	NA	40,000	43,000	4,020.
Other-than-lethal effects.	CNS affected at conc as low as 4 ppm; may induce headache, nausea.	None reported	Irritation of eyes at conc as low as 300 ppm.	None reported	None reported	None reported.
Odor threshold, ppb	0.6	1.3	7,000	20	NA	>1.
Suppliers	NGO, TX; Pennwalt, PA; Phillips, TX; Kodak, NY.	NGO, TX; Pennwalt, PA; Phillips, TX; Kodak, NY.	Ashland, MA and OH.	NGO, TX; Pennwalt, PA; Phillips, TX.	NGO, TX; Pennwalt, PA; Phillips, TX.	NGO, TX; Pennwalt, PA; Phillips, TX.
Price per pound	$1.02 (NGO)	$1.82 (NGO)	$0.75 (Ashland)	NA	NA	NA.
Comments	Widely used as mine stench warning agent and liquid petroleum gas odorant.	Widely used as NG odorant. Odor dissipates quickly. Has moderate odor-strength plateau.	Limited use as mine stench warning agent.	Widely used in NG. Blends with mercaptans. Rarely used in pure form.	Widely used in NG. Blends with TBM (acts as anti-freeze). Rarely used in pure form.	Widely used in NG. Major component in blends with isopropyl mercaptan. Has high freezing point.

Ashland Ashland Chemicals, Inc. CNS Central nervous system. conc concentration. Kodak Eastman Kodak Co. LC Lethal concentration. LD Lethal dose. NA Not available. NG Natural gas. NGO Natural Gas Odorizing Co. Pennwalt Pennwalt Corp. Phillips Phillips Petroleum Co. TWA Time-weighted average.

[1]All listed odorants are readily available, except amyl acetate, which was rated "moderately available."

[2]Hazardous decomposition products of all listed odorants are HS and SO_2, except that this information is not available for amyl acetate.

In addition, available data suggest that THT may be far less toxic than ethyl mercaptan. Although ACGIH and NIOSH have not established a TLV for THT, the lethal concentration (LC_{50}) for inhaled vapors of THT is 44,200 ppm (for rats), compared with an LC_{50} of 4,420 ppm for ethyl mercaptan. Based on this finding, and a NIOSH search of its TOXLINE computerized data bank of toxic substances, the Mine Safety and Health Administration (MSHA) has approved the use of THT in mine stench systems, provided the injection equipment maintains agent concentrations at nontoxic levels. (The substitution of THT for ethyl mercaptan in existing stench systems thus does not satisfy the conditions established by MSHA for the use of THT in mine stench fire-warning systems).

Other pertinent chemical and physical properties made THT a favorable choice for use in the stench system. However, like ethyl mercaptan, THT is flammable (flashpoint 55° F) and needs to be mixed with an inerting agent to avoid possible explosion hazards. This potential hazard is greatest if stench is injected into compressed air. Numerous incidences of compressor fires and explosions have been recorded. Most were caused by ignition sources, such as glowing carbon deposits, igniting combustible lubricating oils inside the compressor, lines, or receiver. The introduction of a flammable liquid (such as a flammable stench odorant) into the compressed air system would only compound the hazard.

Laboratory flammability tests were conducted, and it was determined that a mix of 10 parts Freon 113[4] refrigerant and 1 part THT is totally noncombustible. Accordingly, the stench fluid selected and used throughout the program was a 10:1 mix of Freon 113 and THT.

STENCH INJECTOR DEVELOPMENT

Prior to hardware development, numerous mining companies and mine safety specialists were contacted to help set performance specifications for the improved stench warning system. Both performance-range and general design specifications were thus developed. The specifications are summarized in table 2. The development program began with a comprehensive analysis of existing stench-injection systems.

Existing Stench-Injection Methods

Two methods of stench injection are now in common use: the vial-breaking method and the pressurized-canister method. The vial-breaking method employs a glass vial that contains the stench fluid. The vial is placed inside an airtight steel cylinder (fig. 4), which is connected in parallel to the compressed-air line by two hoses fitted with globe valves. The system is activated as follows: First, the globe valves are opened to allow air to pass over the vial; then, a steel plunger is screwed into the cylinder to break the vial (fig. 5). The broken vial releases the stench fluid into the airstream. The practices of throwing a bottle of stench fluid down the ventilation shaft or "puddling" the fluid at the collar of the downcast shaft are simply modified forms of the vial-breaking method.

Where the pressurized-canister method is used, the stench fluid is contained in a canister pressurized to 400 psi with a fluorinated hydrocarbon propellant (fig. 6). The canister is connected to the compressed-air line or emptied into the ventilation airstream through a short length of tubing (feed line in figure 7). Both systems use an ethyl mercaptan-Freon mix as the stench agent.

Functional analysis and actual experience indicated that neither the vial-breaking method nor the pressurized-canister method was satisfactory because they were fundamentally unable to meet the established performance-range or general design specifications. Alternative design concepts were therefore developed.

Design Concepts

Three design concepts were developed and evaluated relative to the performance specifications: pressurized canister

[4]Reference to specific products does not imply endorsement by the Bureau of Mines.

TABLE 2. - Stench fire-warning system specifications

Performance-range specifications

Airflow, ft^3:	
Ventilation air	50,000-2,000,000
Compressed air	2,000-20,000
Compressed-air pressure, psig	80-150
Stench gas concentration, ppm:	
In compressed-air line	[1]0.5-2.0
In ventilation air	[1]0.1-2.0
Minimum duration of stench injection, min:	
Into compressed air	30
Into ventilation air	10
Air temperature, °F:	
Ventilation	-30-125
Compressed	-30-200
Equipment operating specifications:	
Temperature, °F	-30-125
Humidity, pct	20-100
Vibration (applied)	None
Environmental corrosion, pH	4.0-9.0

General design specification

Reliability	Extremely high. (System should be simple with a minimum number of moving parts.)
Life expectancy	Indefinite with periodic maintenance.
Ease of operation	Simple--requiring minimal training.
System status indication	Visual, including "Ready to operate," "Operating correctly," and "Needs to be refilled."
Injector costs, maximum:	
Hardware	[2]$4,900
Installation, worker-h	8
Maintenance, worker-h/month	0.5

[1]As an added safequard, the maximum design concentration of THT is the same as that of ethyl mercaptan, even though available data suggest that THT is far less toxic.

[2]Median from field survey; however, a much lower figure is probably more realistic. This figure does not include telemetry for remote injector activation, although telemetry may represent the single largest expense for remotely operated systems.

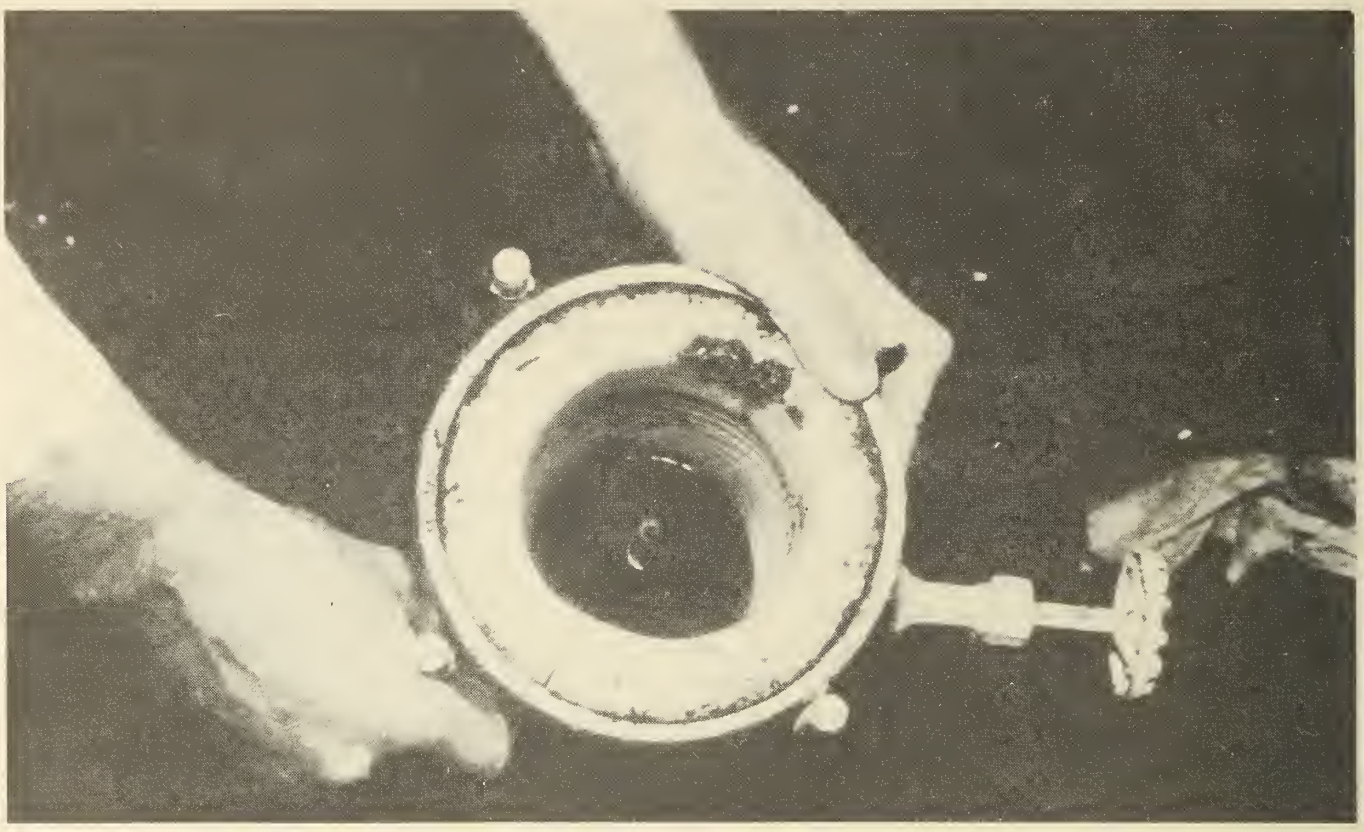

FIGURE 4. - Vial-breaking stench injector.

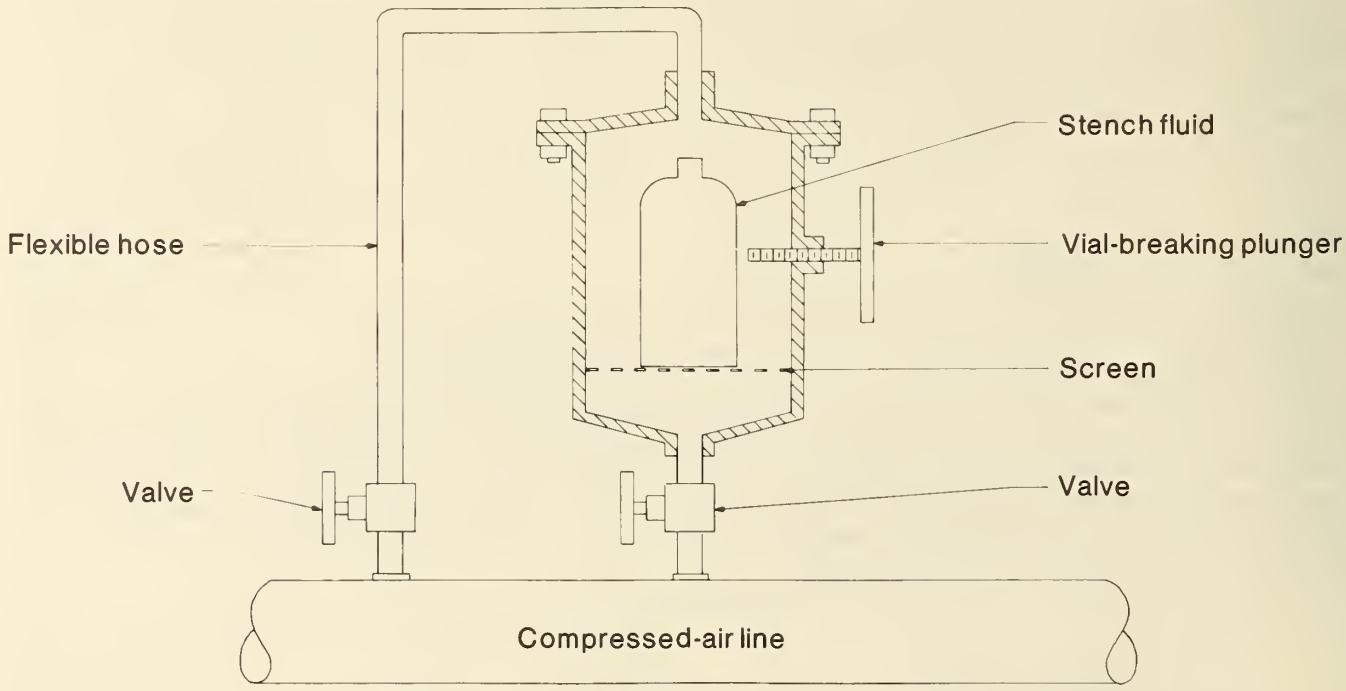

FIGURE 5. - Components of vial-breaking stench injector.

FIGURE 6. - Pressurized-canister stench injector.

with metering orifice, pressure balanced with metering orifice, and variable-rate injection pump. Each of these concepts is described below.

Pressurized Canister With Metering Orifice

This concept, which provides for metering of the stench flow, is a logical extension of the pressurized-canister injection method already in use. The metering capability could be added simply by installing a metering orifice in the stench-delivery tube of a pressurized-canister injector (fig. 8).

Although the design is simple and in theory could satisfy the system performance specifications, injector reliability would be low. Low reliability would result because an extremely small orifice would be required to meter the contents of the pressurized canister (at 400 psi) into the airstream over the desired time period (10 min for ventilation air; 30 min for compressed air). Internal canister pressurization to at least 400 psi is necessary to assure complete discharge of the canister contents. Orifices sized 0.001 to 0.013 in would be required to achieve the desired stench flow rates. Particles as small as 25 μm could plug an orifice of this size, and the probability of encountering particles 25 μm in diameter or larger is very high, even in a clean environment. Since nothing approaching clean-room conditions exists at a typical mine, the chances of a plugged

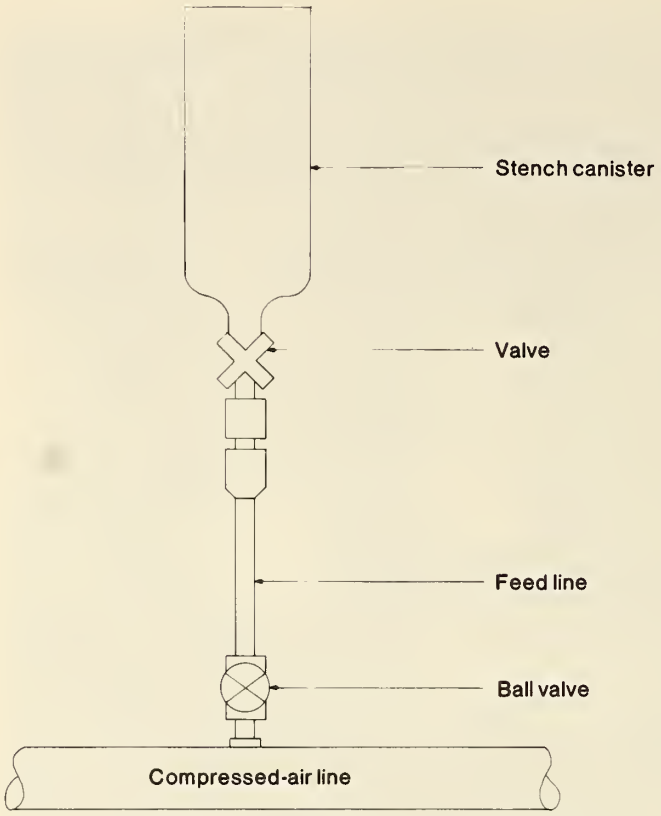

FIGURE 7. - Components of pressurized-canister stench injector.

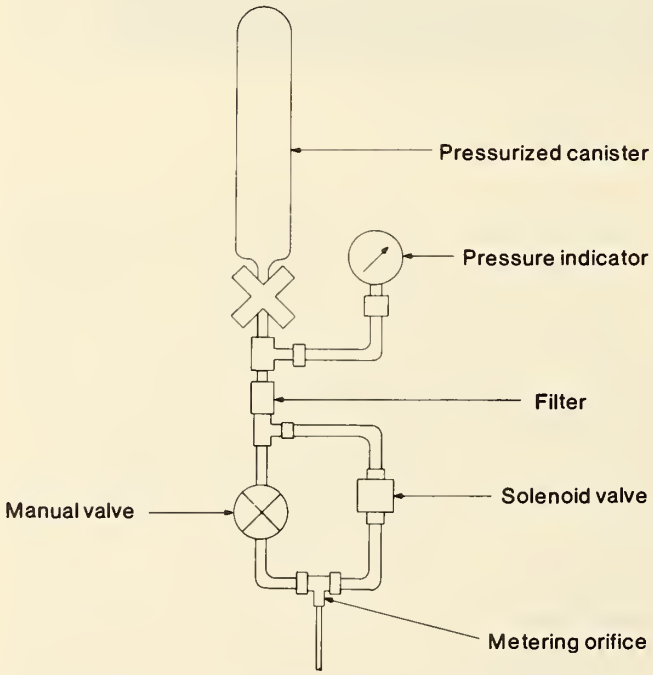

FIGURE 8. - Pressurized-canister injector with metering orifice.

orifice (and, therefore, an interrupted stench discharge) are also very high. In addition, a wide variation in stench flow rate would result owing to canister propellant pressure decay. The flow rate could be expected to vary by as much as 50 pct over the period of the discharge.

Pressure Balanced With Metering Orifice

The pressure-balanced concept was developed to take advantage of the positive features of the previous concept while eliminating its undesirable features. Orifices much larger than those mentioned above can be used if the high pressure differentials across the orifice are eliminated. This can be accomplished by introducing line pressure on both sides of the orifice via a pressure-balancing line. The concept is illustrated in figure 10. The pressure difference between point *1* in figure 9 (just below the orifice at the entry to the pressure-balancing line) and point *2* (at the bottom of the standpipe) is negligibly small.

During steady-state flow, the fluid pressure at point *2* is also roughly equal to the air pressure at point *1* because the fluid pressure and air pressure at point *2* are in equilibrium. Since the fluid pressure at point *2* is roughly equal to the air pressure at point *1*, the driving head exerted at the orifice is equal *only* to the weight of the column of fluid between point *2* and the orifice. This driving head remains constant for nearly the entire discharge, meaning the flow through the orifice (the stench-injection rate) is also constant during nearly the entire discharge.

During startup, before the standpipe is emptied of stench mixture, the flow rate is greater than the steady-state flow value. This does not last very long and is easily minimized by making the standpipe cross-sectional area as small as possible. When the stench-mixture surface drops below the tip of the standpipe near the end of the run, the flow rate begins to decrease, since effective head decreases. Eventually, both the flow rate and effective head drop to zero.

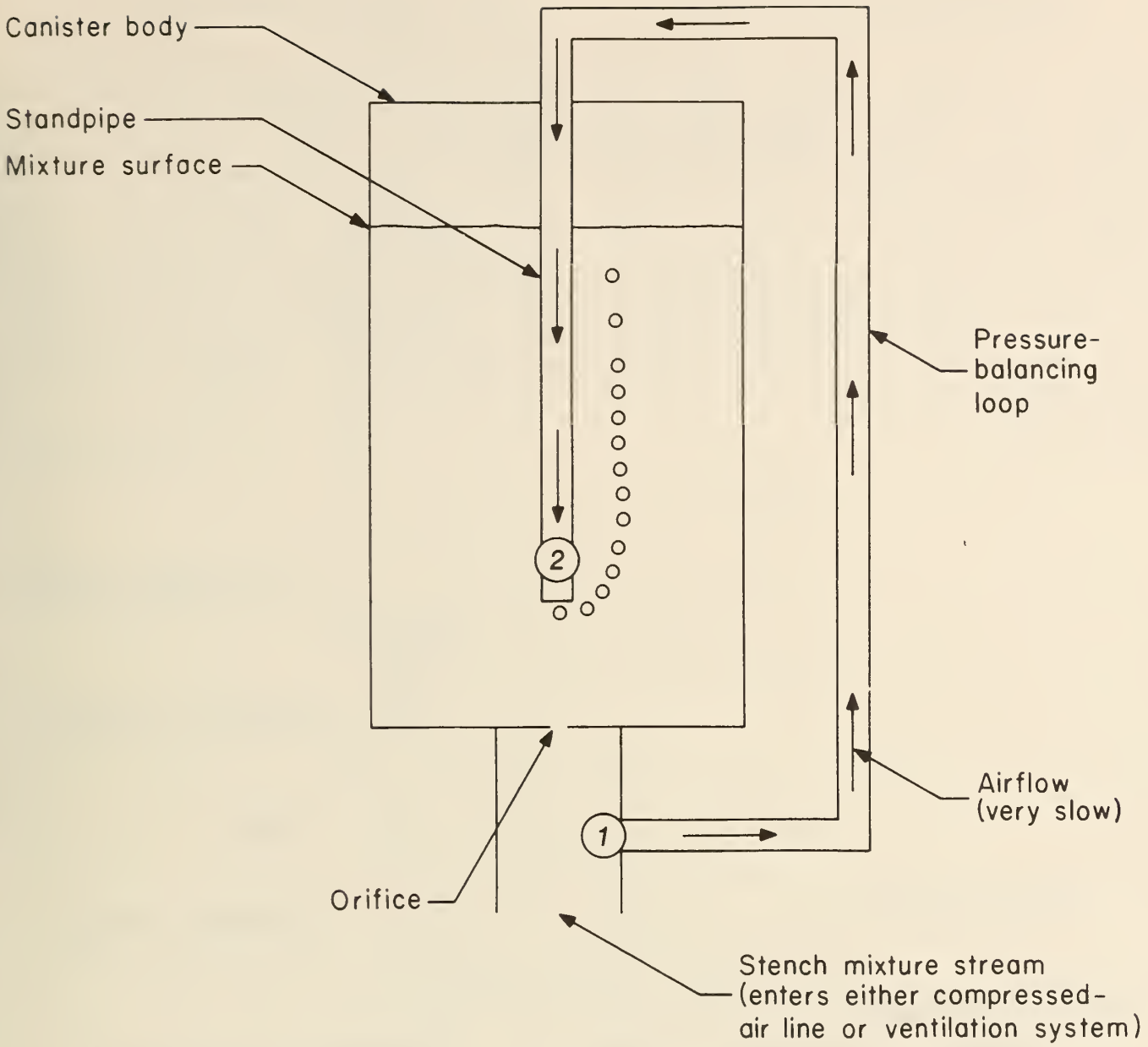

FIGURE 9. - Use of pressure-balancing line to equalize pressure across metering orifice.

This effect can be lessened by minimizing the internal area of the canister below the tip of the standpipe.

The important features of this concept are as follows:

1. The pressure below the orifice is balanced by an equal pressure above the orifice so that the pressure of the airstream into which the stench is injected has no affect on injector operation.
2. The driving head across the orifice is very low, so the size of the orifice can be relatively large (0.015 to 0.070 in) and still achieve the desired stench flow rates.
3. The driving head is independent of the amount of stench fluid in the injector canister. Therefore, the injection rate does not decay as the fluid level in the canister drops.

Variable-Rate Injection Pump

The variable-rate injection pump concept is the most precise method for stench injection. A precision diaphragm metering pump placed between the stench canister and the airstream can effectively control stench-fluid flow rates to extremely close tolerances (fig. 10). The primary disadvantages of this system are its complexity and its reliance on electric power. These factors could lead to very low system reliability. In addition, the cost of such a system would be quite high compared to that of the other two concepts.

Concept Evaluation

The three design concepts were subjected to a systematic evaluation to weigh their respective advantages and disadvantages. The concept-evaluation matrix showing the parameters evaluated and the resultant ratings is shown in table 3. Based on this evaluation, the pressure-balanced with metering orifice concept was selected for further development. Detailed design and prototype fabrication followed. A drawing of the resulting injector is shown in figure 11, and operating data are shown in table 3.

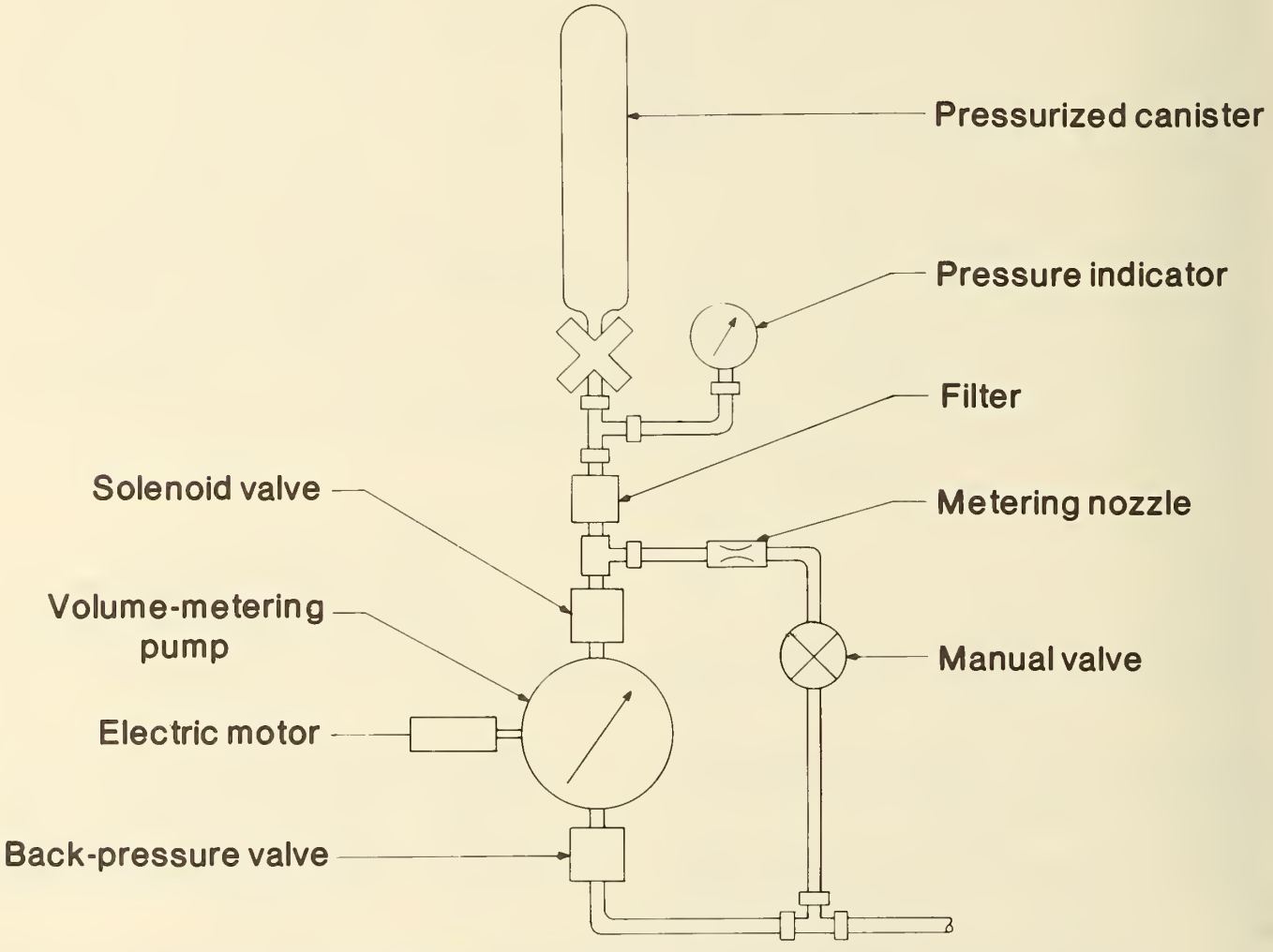

FIGURE 10. - Variable-rate injection pump.

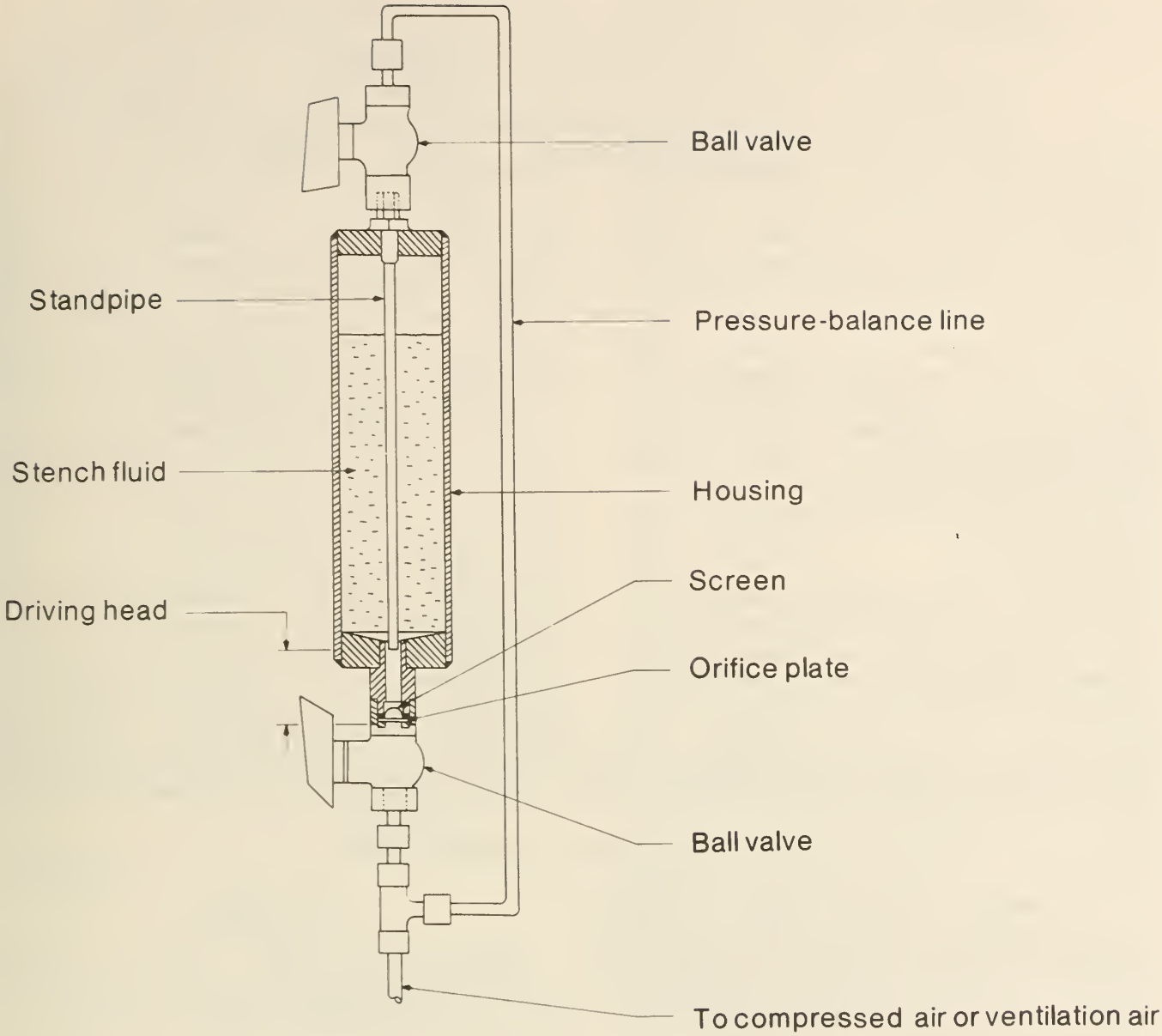

FIGURE 11. - Improved stench injector design.

TABLE 3. - Evaluation matrix for new injection-method design concepts

Parameter	Pressurized canister with metering orifice		Pressure balance with metering orifice		Variable-rate injection pump	
	Rating	Value[1]	Rating	Value[1]	Rating	Value[1]
Stench concentration range.	Acceptable	3	Acceptable	3	Acceptable	3
Complexity.....	Low.....	3	Low.....	3	Medium....	2
Filtration level required	Very high.	0	Medium....	2	High.....	1
Number of injector sizes required.	5.....	1	3.....	2	2.....	3
Status indication.....	Fair.....	2	Fair.....	2	Poor.....	1
Ease of manual operation.	Good.....	3	Good.....	3	Good.....	3
Initial cost, estimated..	$800.....	3	$1,800....	2	$3,000....	1
Operating cost, estimated	$100.....	2	$50.....	3	$100.....	2
Number of significant leak points.	15.....	1	1.....	3	15.....	1
Electric power required..	([2]).....	3	([2]).....	3	Yes.....	1
Remote-operation capability.	Yes.....	3	Yes.....	3	Yes.....	3
Temperature sensitivity..	High.....	1	Low.....	3	Medium....	2
Reliability.....	Very low..	0	High.....	3	Low.....	1
Maintainability.....	High.....	3	High.....	3	Low.....	1
Training requirements....	Low.....	3	Medium....	2	High.....	1
Life expectancy.....	High.....	3	High.....	3	Low.....	1
Safety.....	Medium....	2	High.....	3	Low.....	1
Total.....	NAp.....	36	NAp.....	46	NAp.....	28

NAp Not applicable. [1]Maximum total = 51. [2]For remote-operation capability only.

TESTING THE IMPROVED STENCH SYSTEM

A prototype of the entire improved stench system was fabricated and proof-of-concept tested in the laboratory and at an operating underground mine to validate its performance and highlight any design deficiencies.

LABORATORY TESTING

The system was thoroughly tested following fabrication. Tests involved discharges of nonodorized liquids as well as the THT-Freon 113 mixture selected for stench warning use. Tests in both ventilation-air and compressed-air streams were performed. Parameters measured included fluid flow rates, discharge times, and stench concentrations in the airstreams. All tests indicated conformance with the system performance specifications (table 2).

FIELD TESTING

The improved stench system was field tested at Kerr-McGee Corp.'s Church Rock No. 1 uranium mine near Gallup, NM.

Mine Ventilation and Compressed-Air Analysis

The improved stench system releases odorant into both the ventilation-air and compressed-air streams, relying on these airstreams to transport the warning signal to the various workplaces. Therefore, a thorough knowledge of these systems and their interactions was essential in order to plan and lay out an effective stench warning system.

The test mine has two main levels, designated 1-4 and 1-5, the 1-5 level being about 300 ft below the 1-4. Raises are

driven from these levels to the ore, which is 50 to 100 ft above the level in each case. Figure 12 presents the layout of the haulage levels, along with the locations and flow rates of the ventilation shaft and boreholes.

The ventilation scheme has intake air downcasting through the main shaft and borehole 6 to the haulage levels. The air travels along the haulage drifts, up the raises, through the stopes, and finally through a network of exhaust drifts in the ore horizon and out the exhaust boreholes. Exhausting fans are located on the surface at the exhaust boreholes.

For both ventilation purposes and administrative reasons, the 1-4 level of the test mine is divided into two segments. The area to the east of the two air doors (fig. 12) has its own hoisting plant, compressed-air supply, and ventilation system. The two doors form an airlock and are normally closed; however, there is a minor leakage flow from the east side to the west. The two compressed-air systems are connected, and there is normally a small net flow, again from east to west. Thus, the stench

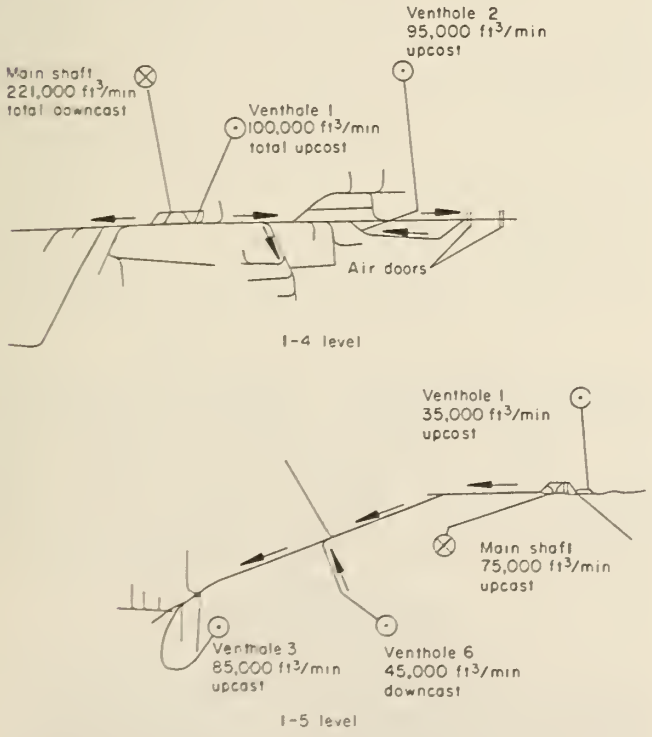

FIGURE 12. - Layout of haulage levels, boreholes, and main shaft in test mine.

tests were conducted in the west side of the mine without disturbing the east side.

A tracer gas technique was used to determine the effectiveness of the compressed-air system in transporting the warning signal. The tracer gas was released at the point where the new stench injector was to be installed, at 9:55 a.m., a time when compressed-air usage is usually at a maximum. Starting at 10:00 a.m., air samples were taken at 3-min intervals for 30 min, at four locations underground and on the surface at venthole 1.

Tracer gas was detected at all sampling points. The locations of the sampling points as well as the transit time of the tracer gas to each point are indicated in figure 13.

The rapid appearance of the tracer gas in the exhaust borehole (after 8 min) indicated that leakage from the compressed-air line into the ventilation air was originating not very far downstream from the injection point and that the stench first reached most areas of the mine through the ventilation air rather than in the compressed air. It is also probable that a large percentage of the stench injected into the compressed-air line was exhausted through venthole 1 after having passed through only a small part of the total workings. However, some stench was retained in the compressed air, indicating that this mode of stench transport can effectively supplement ventilation-air transport.

Injector Locations and Installation

Ventilation-air injectors were installed at each of the two intake-air shafts. One injector was installed in a crawl space located just below ground level near the top of the main shaft (fig. 14). Because there was a high rate of activity near the employee and supply hoist, the crawl space location was chosen to minimize the possibility of accidental system activation. Approximately 10 ft of copper tubing was suspended from the injector down into the shaft to carry the stench agent.

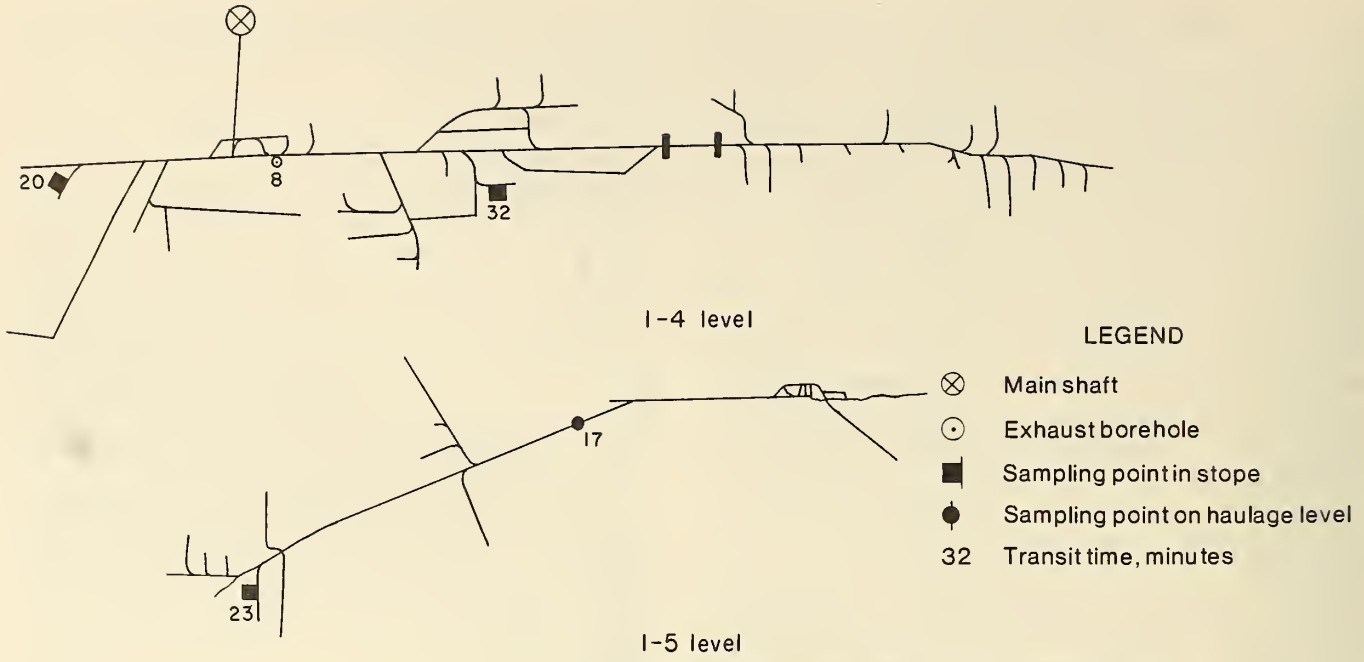

FIGURE 13. - Sampling points and transit times for compressed-air system tracer gas analysis.

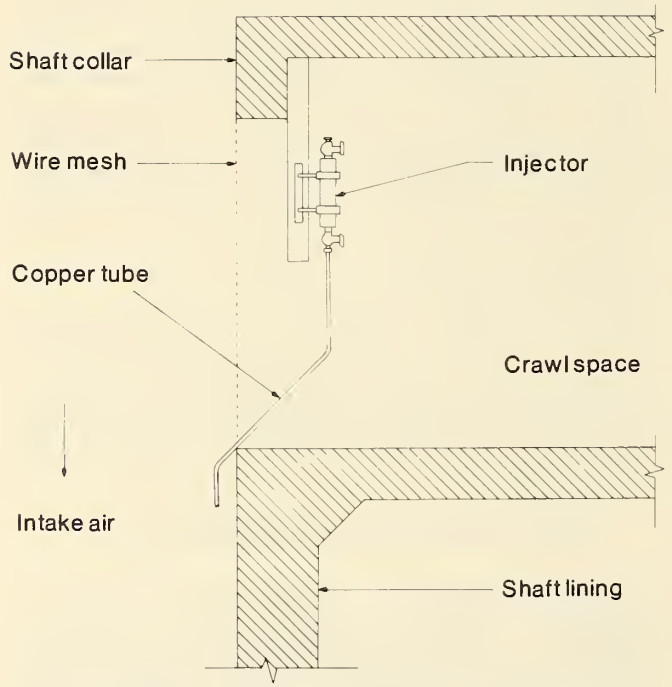

FIGURE 14. - Main shaft ventilation-air injector location.

The other ventilation-air injector was installed on a leg of an emergency-escape-hoist headframe positioned over venthole 6 about 1 mi from the main shaft (fig. 15). This injector was mounted approximately 7 ft above ground level to discourage tampering.

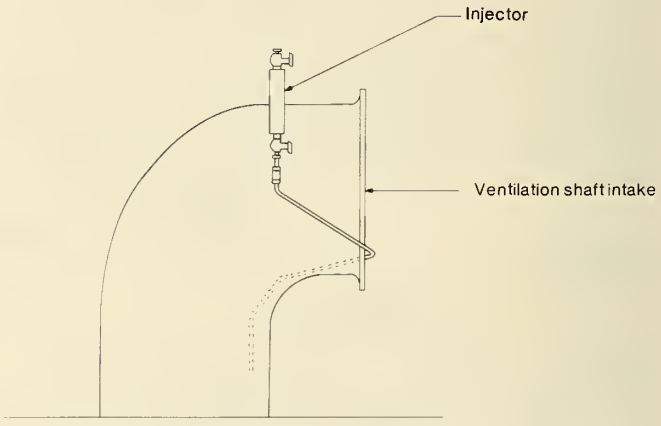

FIGURE 15. - Remote venthole injector location.

The compressed-air injector was mounted on the main receiver for the compressed-air system (figs. 16-17). A piece of copper tubing approximately 2 ft long joined the injector to the main compressed-air line through a shutoff valve.

Test Procedures

The in-mine test consisted of using the improved stench system to issue the warning signal during two regularly scheduled fire drills. The mine's routine practice was to conduct drills during all three

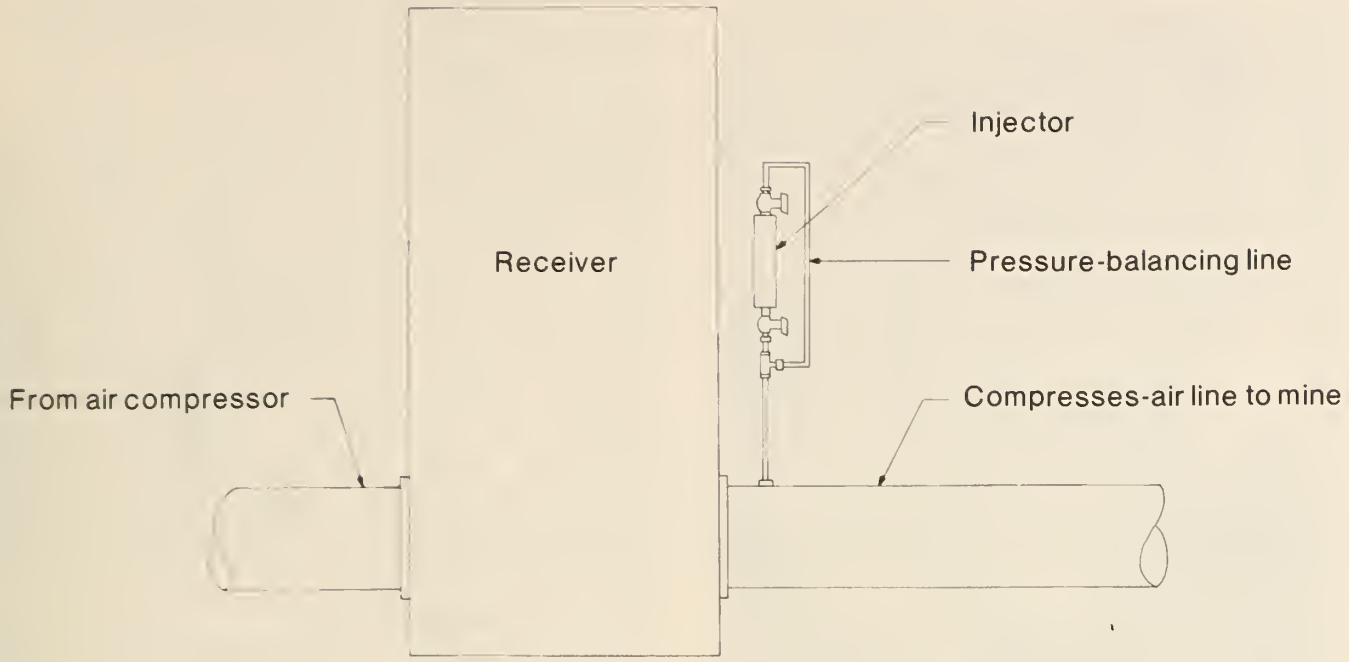

FIGURE 16. - Compressed-air injector location.

shifts over the course of 1 week. The improved system was used for the drill during the first shift (day shift) and for the second-shift (afternoon) drill. For comparison, the mine's existing vial-breaking system was used for the third-shift drill. This arrangement afforded the opportunity to evaluate and compare the performance of the two systems under constant mine conditions.

The emergency plan at the mine is different from that of most mines in that it does not call for immediate evacuation. Standard procedures require miners to proceed to a dead-end drift or stope with an air line and build a barricade.

The standard procedure for fire drills (of which the miners are always informed beforehand) requires miners to note the time they smell stench and proceed to a dead-end drift or stope with an air line and barricade materials. (Barricades are not actually built.)

Environmental samplers visit each work area and fill out a form showing the location of each worker, the time he or she smelled stench, the strength of the stench, the action taken by the miner, and the miner's comments. This procedure was followed during all tests.

Results

The main criteria for evaluating the performance of the improved stench system were (1) degree of coverage, (2) elapsed time between actuation of the injectors and the detection of odor at various locations, and (3) stench concentrations measured at various locations.

To give an overall view of the performance of both the improved system and the existing system, stench transit times to various areas of the mine were plotted on maps of the haulage levels. These transit times were based on the stench arrival times recorded by the mine's environmental samplers during the drills.

Figures 18-21 show the results of the tests of the improved system (during the first- and second-shift drills and on both haulage levels.) Figures 22 and 23 show the results of the test of the existing system during the same week. Since this test was run on the third shift, there were fewer active workplaces for which arrival times could be recorded. Therefore, the results of two earlier tests of the existing system were reconstructed from mine records to provide a better comparison of the old

FIGURE 17. - Compressed-air injector mounted on receiver tank.

and new systems. The earlier tests of the mine's existing system are illustrated in figures 24-27.

During the first-shift test of the improved system, air samples were taken at several locations in the mine while the stench was noticeable at those locations. These samples were then analyzed to obtain their quantitative stench concentrations (expressed as parts per million of THT in air). The locations of the sampling points are shown in figure 28. Stench concentration versus time is plotted in figure 29. Figure 29 also shows the upper and lower system design limits for stench concentration (from table 2). Only 2 of the 10 samples collected exceeded the 2.0-ppm upper design limit, and no samples fell below the 0.1-ppm lower design limit.

Of 23 miners who were interviewed during the second-shift test of the improved system, only 2 rated the stench as reaching an annoying level, and none rated it as reaching a sickening level, indicating that odorant levels were probably very near the 2.0-ppm design goal. One environmental sampler commented that the miners thought the new stench (THT) was not as sickening as the old (ethyl mercaptan).

Mine management was pleased with the improved system not only because of improvement in warning times, but also because of the ease and simplicity of operation of the new injectors. The valve

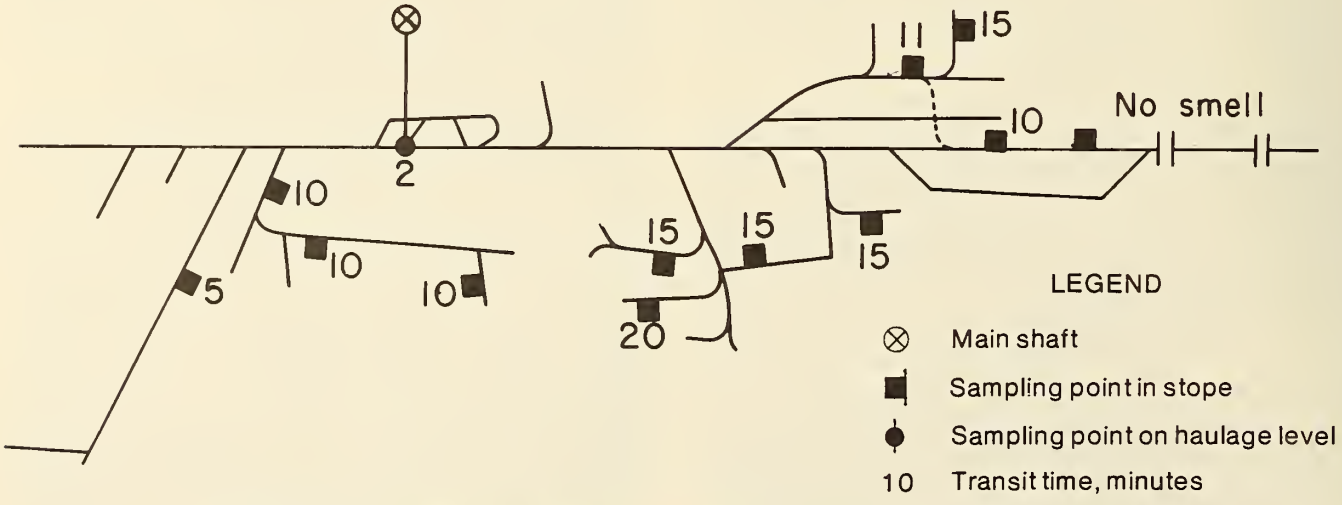

FIGURE 18. - Stench test results, improved system, first shift, 1-4 level.

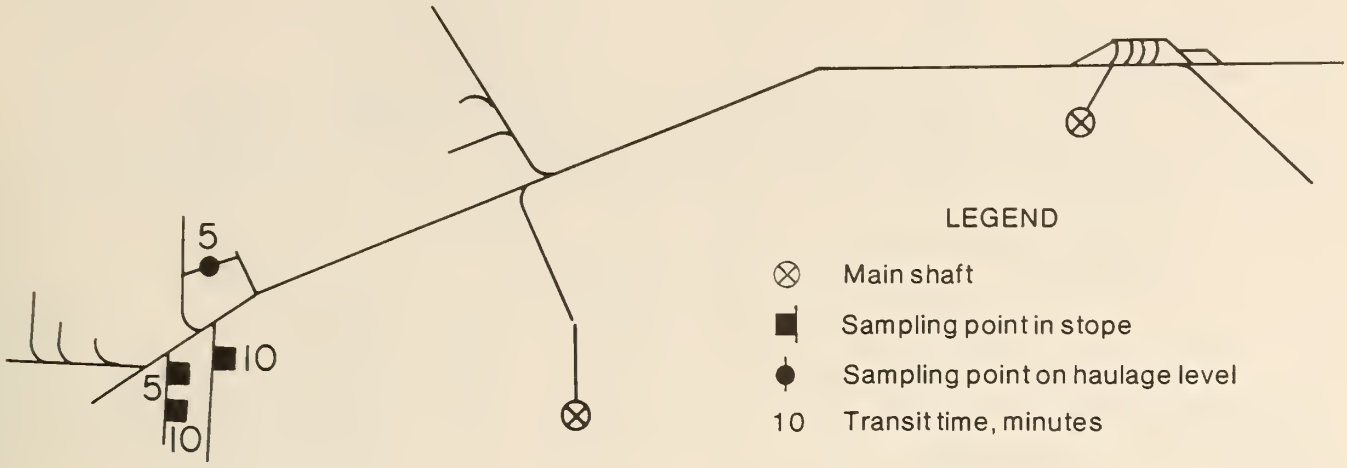

FIGURE 19. - Stench test results, improved system, first shift, 1-5 level.

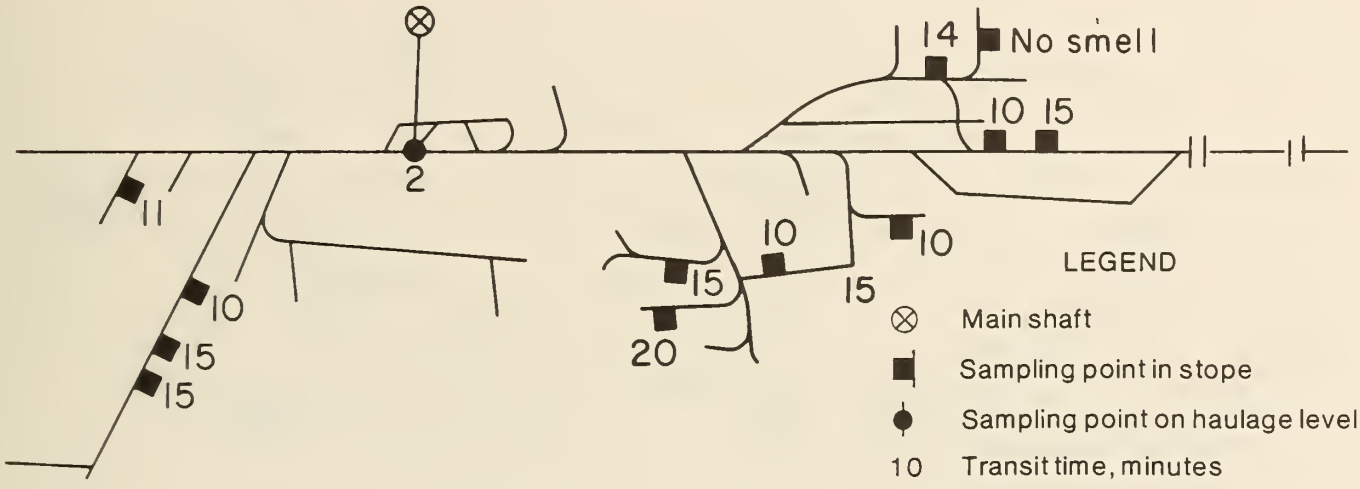

FIGURE 20. - Stench test results, improved system, second shift, 1-4 level.

FIGURE 21. - Stench test results, improved system, second shift, 1-5 level.

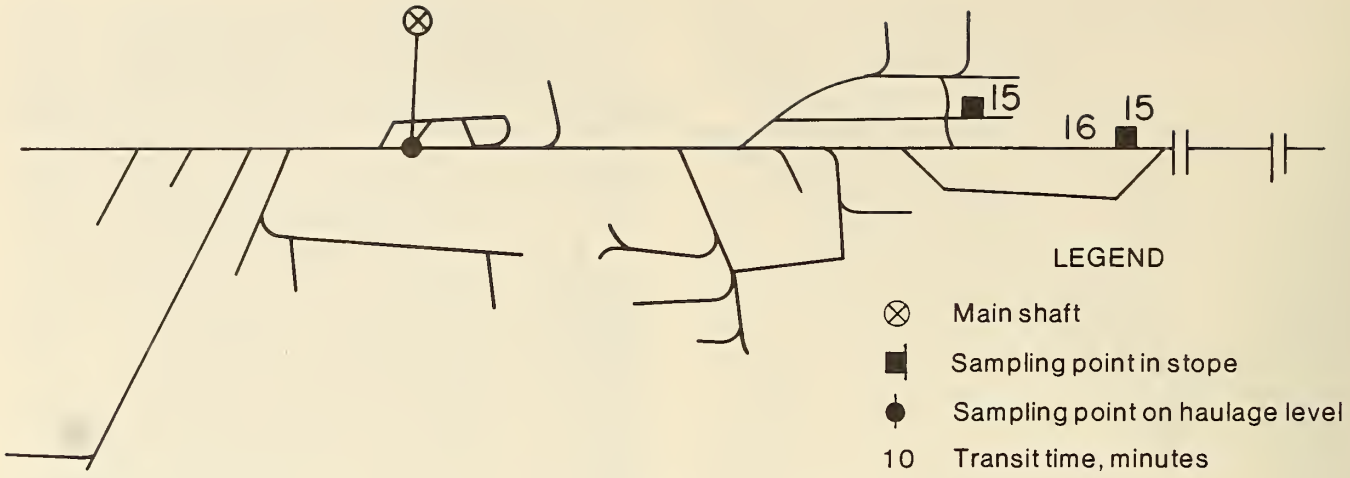

FIGURE 22. - Stench test results, existing system, third shift, 1-4 level.

FIGURE 23. - Stench test results, existing system, third shift, 1-5 level.

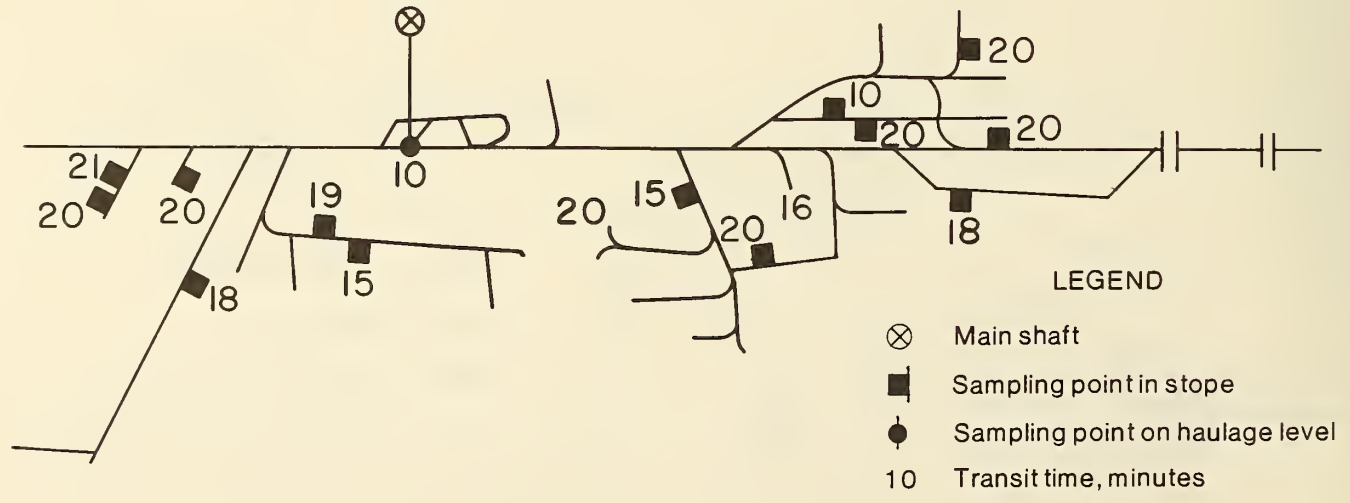

FIGURE 24. - Previous stench test results, existing system, first shift, 1-4 level.

FIGURE 25. - Previous stench test results, existing system, first shift, 1-5 level.

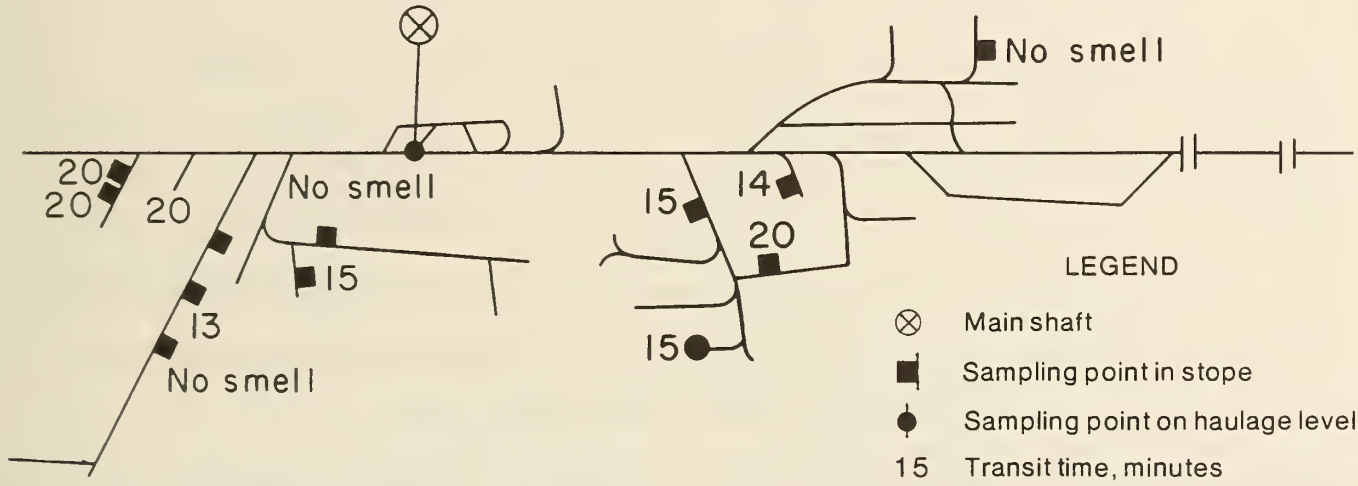

FIGURE 26. - Previous stench test results, existing system, second shift, 1-4 level.

FIGURE 27. - Previous stench test results, existing system, second shift, 1-5 level.

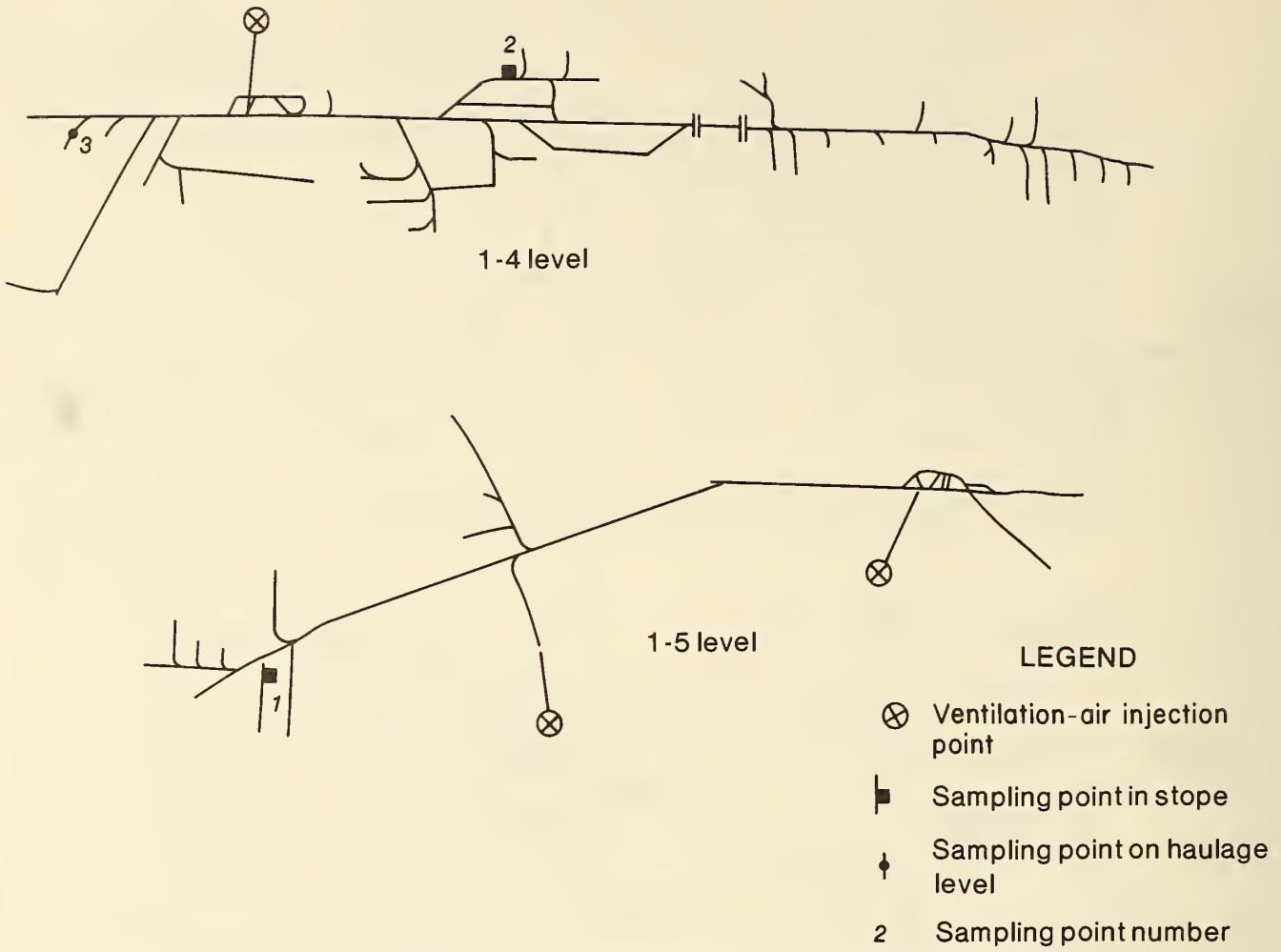

FIGURE 28. - Locations of air sampling points.

stem that breaks the vial in the existing system is very difficult to turn. In addition, it is necessary to open two globe valves whose positions are not readily apparent. The improved system, which requires only the manipulation, in any order, of two easy-to-turn 90° valves, was regarded as far superior.

The most dramatic improvement in transit times occurred at the western end of the 1-5 level. No doubt this was due to the injection of stench into intake ventilation air at venthole 6. Substantial improvement also occurred at the western end of the 1-4 level. This was probably due to the injection of stench into the intake air at the main shaft. In the central area of the 1-4 level, transit times for the two systems were about the same. The reason for this may have been that when the existing system was used, stench reached this area by leakage from the compresssed-air system into the ventilation air. This hypothesis is supported by the rapid appearance of tracer gas that was observed in venthole 1 during the tracer gas test of the compressed-air system. Both systems had some trouble providing rapid coverage to the area near the eastern boundary of the 1-4 level. This area is at the extremes of both the ventilation and compressed-air systems. Changes in the ventilation system to increase airflow to these areas would probably improve coverage of these areas.

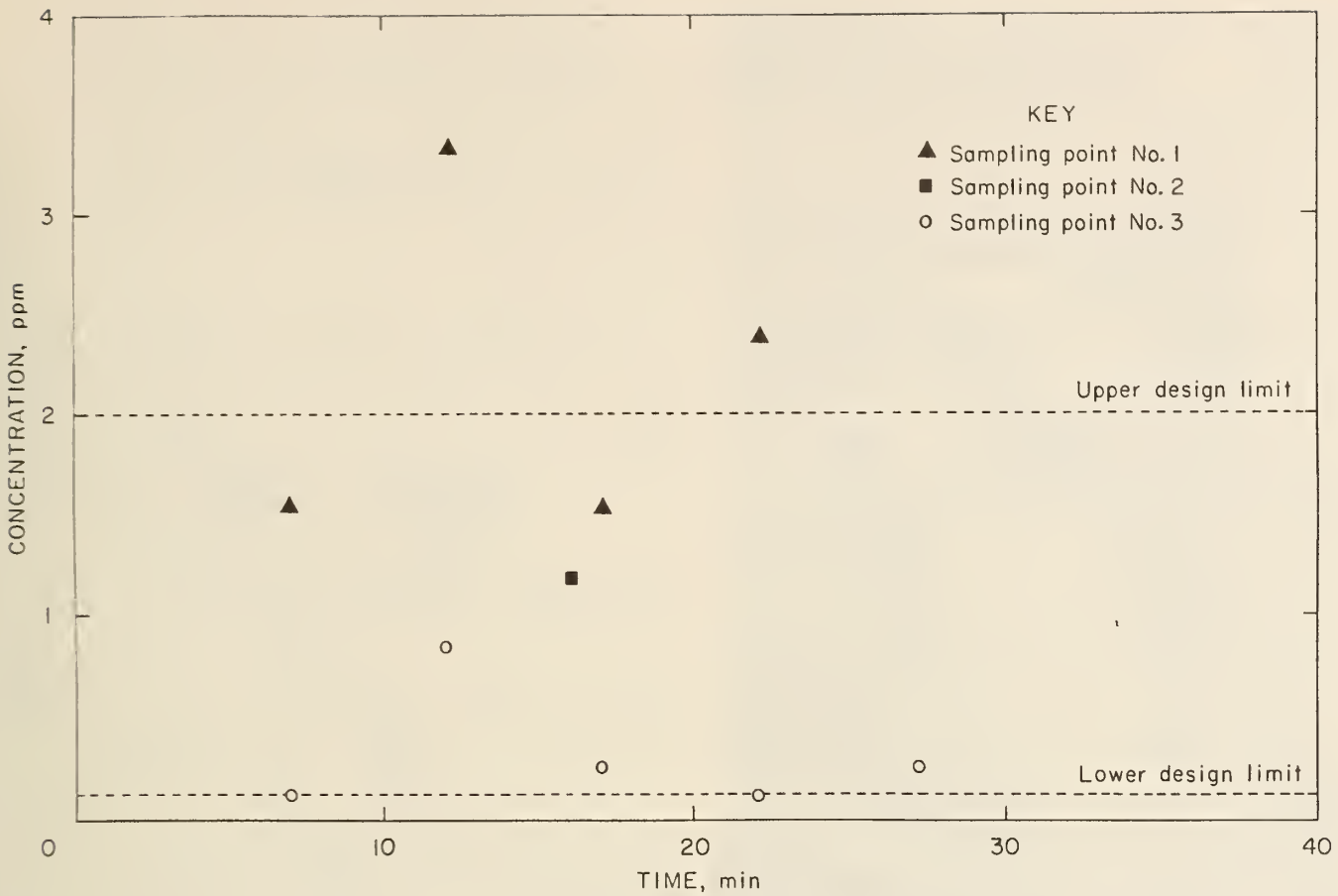

FIGURE 29. - Stench concentration versus time for air samples collected during stench tests.

DESIGN AND DEVELOPMENT OF SECOND-GENERATION STENCH INJECTOR

Field testing of the prototype stench system was successful in that the injectors performed according to specification, providing faster, more consistent, and more controlled concentrations of stench in the mine. However, the field testing also highlighted certain design aspects of the injector needing improvement.

DEFICIENCIES IN DESIGN OF THE IMPROVED STENCH INJECTOR

The following deficiencies in the design of the improved stench injector were noted:

1. Fluid levels in the canister body were not visible, and valve positions alone are not a reliable indicator of system readiness. An injector design that permits visual system status checks is needed.

2. Refilling the injectors was a nuisance. The injectors had to be removed from the mounting brackets and refilled from a special container (fig. 30).

3. The injector had to be removed from the mounting bracket and dismantled to inspect the orifice and screen.

4. Because two valves have to be opened, operation of the injector by remote control is somewhat complicated. (Remote-control injector operation is an extremely attractive feature under certain circumstances. In the field tests of the improved system, significantly shorter stench transit times were achieved in the part of the mine near the remote downcast vent shaft, due to the injection of stench into the ventilation

FIGURE 30. - Refilling improved stench injector.

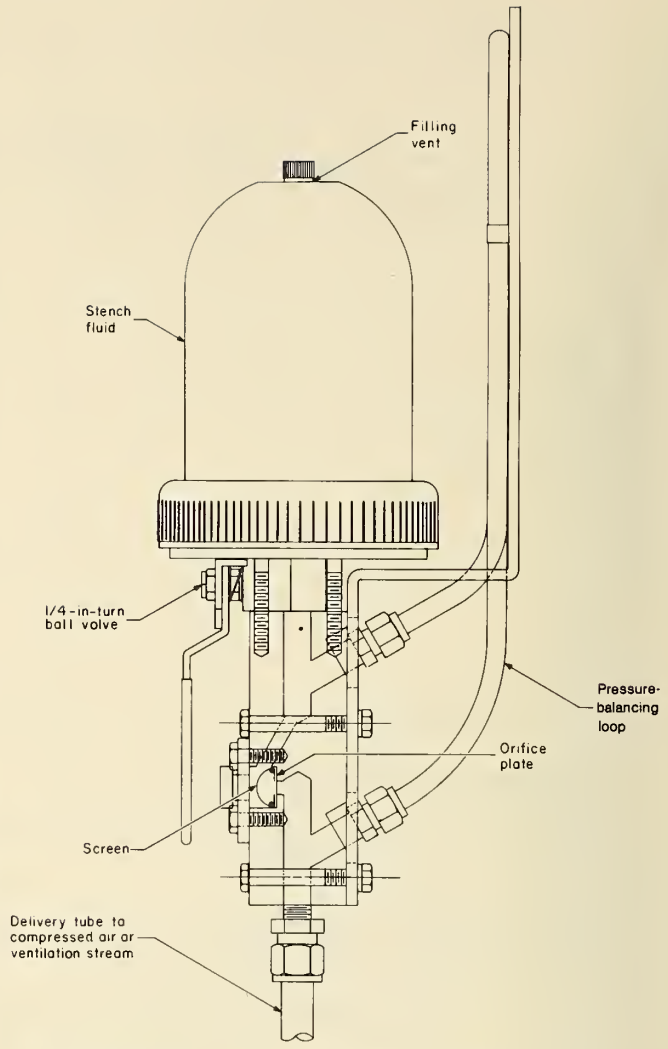

FIGURE 31. - Second-generation stench injector design.

airstream at this location. But this time advantage would be lost if someone had to travel to the remote shaft during a mine emergency to manually operate the injector. The need for remote operation is particularly acute where distance and/or inclement weather make timely access to a remote site impossible.)

5. The overall cost of the injector ($1,800) was judged to be too high.

DESIGN FEATURES OF THE SECOND-GENERATION INJECTOR

The deficiencies listed above formed the basis for additional performance and general design specifications. Based on these additional specifications, a second-generation stench injector design was developed (fig. 31). Although functionally identical to the original injector, the second-generation unit also satisfies these additional requirements:

1. The canister body for ventilation-air injectors is made of clear polycarbonate, permitting visual inspection of the injector fluid level. Also, during injector operation, bubbles can be seen rising through the fluid--proof positive of unhindered fluid flow.

2. A refilling standpipe permits refilling without removing the injector from the mounting bracket (fig. 32).

3. The orifice plate and screen can be quickly inspected through a port on the side of the injector.

4. The injector is operated by a single easy-to-turn 90° ball valve, thus facilitating remote-control actuation.

5. Widespread use of commercial components reduces the overall cost of the injector.

REMOTE-CONTROL SYSTEM FOR INJECTOR ACTUATION

As previously noted, improvements in stench times were greatest near the remote vent shaft. To insure that this rapid warning could be duplicated in an actual emergency, some form of remote-control injector operation would be required.

The following performance specifications were developed to guide the design of a remote system:

1. The system telemetry must be wireless or hard-wired, as conditions dictate.

2. The system must provide positive feedback to the operator to indicate successful actuation of the injector(s).

3. The system must be capable of manual operation should remote operation fail.

4. The system telemetry must be capable of being tested for continuity without actuating an injector.

5. The system must provide emergency backup power to insure proper system function if mine power is lost.

6. The system must be designed in accordance with appropriate MSHA and National Fire Protection Association (NFPA) standards covering warning systems.

7. The system must be designed to operate reliably in harsh mine environments and not be adversely affected by dust, high humidity, varying temperatures, and electrical transients.

8. The system must be capable of remotely actuating one injector with the capability to add additional remote units if desired.

The remote system described below was designed to satisfy the specific requirements of the Kerr-McGee Church Rock No. 1 Mine, where the second-generation stench system was field tested. However, the concept for the remote system is flexible and can be adapted to suit differing local conditions.

FIGURE 32. - Refilling second-generation injector.

Since no power or phone lines connect the site of the remote vent shaft with the mine office, a wireless (radio-frequency) remote-control system was selected. Wireless signal transmission between the two sites was provided by a digital-scan-type telemetry system utilizing frequency-shift-keyed (FSK) tone telemetry. VHF FM radio transceivers were used to transmit signals between the two sites.

Signals were transmitted between the two sites continuously to verify the functional readiness of the telemetry system. Fault lights were provided on a master control panel (master panel) to indicate telemetry failure, power loss, etc. Battery backup power was provided at the master panel and at the remote site.

Operation of the remote injector was accomplished by depressing a button on the master panel. A digital coded signal was transmitted to the remote site, where it was received, decoded, and verified. The valve on the injector was then rotated. The rotation of this valve initiated the stench release and also tripped a switch that prompted the transmission of a return digital coded signal to the master panel. When the return signal was decoded and verified, a light appeared on the master panel, indicating that the injector valve had been operated.

TESTING OF SECOND-GENERATION STENCH SYSTEM

Prototypes of all the second-generation stench system components, including the remote system, were built and proof-of-concept tested in the laboratory and in the Church Rock No. 1 Mine. The in-mine tests of the complete system are summarized below.

INSTALLATION

One complete second-generation stench system, consisting of one manual compressed-air injector (fig. 33), one manual ventilation-air injector for the main shaft (fig. 34), and one wireless remote-control injector for the remote vent shaft (fig. 35) was installed at the Church Rock Mine. Antennas for the remote system were installed on top of the emergency-escape-hoist headframe at the remote site and on the roof of the hoist building near the main shaft. The two antennas were in a direct line-of-sight. The master panel (fig. 36) was installed in the hoist building within sight of the hoist operator. The telemetry equipment at the remote site (fig. 37) was mounted on a leg of the emergency-escape-hoist headframe near the injector.

TEST PROCEDURES

Following hardware checkout, two functional (fire-drill) tests of the system were conducted, one during the first shift and one during the second. (The mine was not working a third shift at the time of these tests). For both tests, all three injectors were actuated simultaneously. The main shaft and compressed-air injectors were operated manually. The injector at the vent shaft was actuated remotely at the same time by depressing the button at the master panel.

RESULTS

All three injectors and the remote actuation system performed according to the specifications. The injector at the main shaft had a release time of 11-1/2 min, the injector at venthole 6 took 12-1/2 min, and the compressed-air injector took 32 min. The light on the master panel indicated successful actuation of the remote injector about 10 s after the release button was depressed.

The main criteria for evaluation of the second-generation stench system were (1) degree of coverage and (2) elapsed time between actuation of the injectors and the detection of the odor at various locations. Since the test conditions were almost identical to those present during the first-generation injector tests, air samples were not collected and analyzed for stench concentration.

FIGURE 33. - Second-generation injector for compressed air.

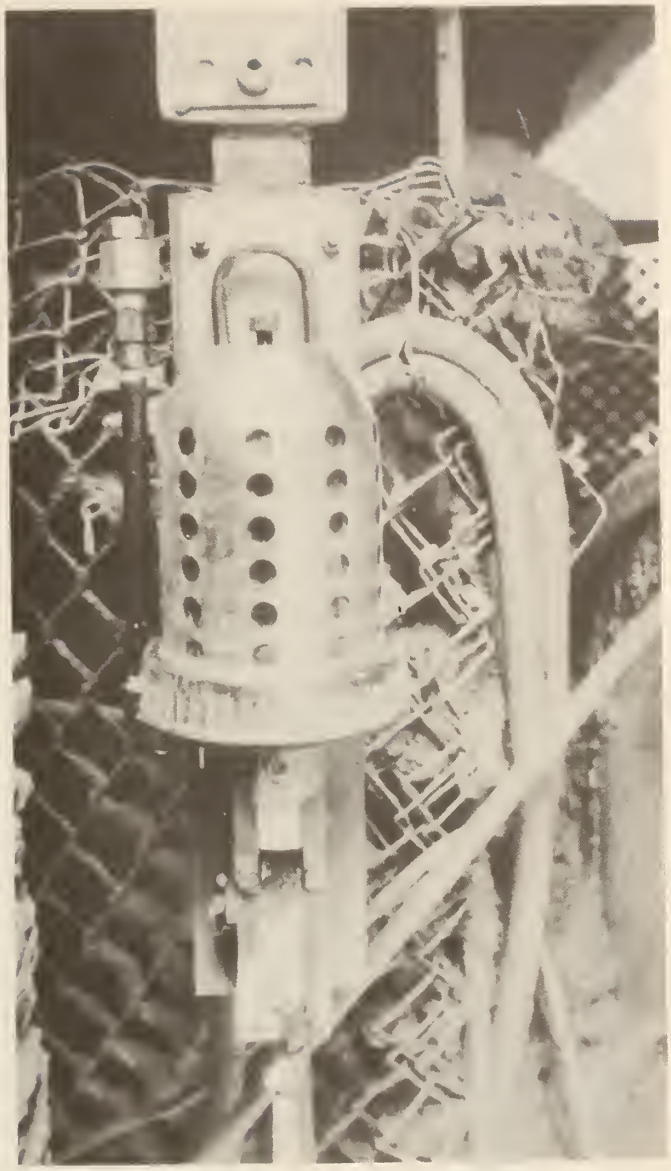

FIGURE 34. - Second-generation injector for ventilation air installed at main shaft.

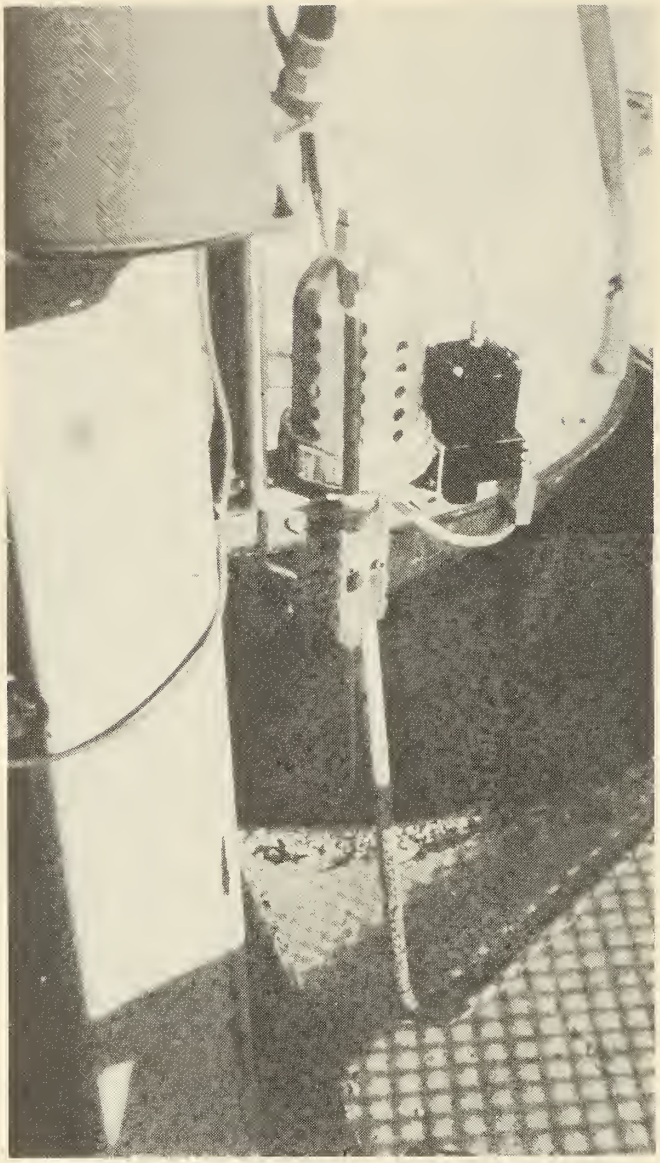

FIGURE 35. - Wireless remotely controlled stench injector for ventilation air installed at remote venthole.

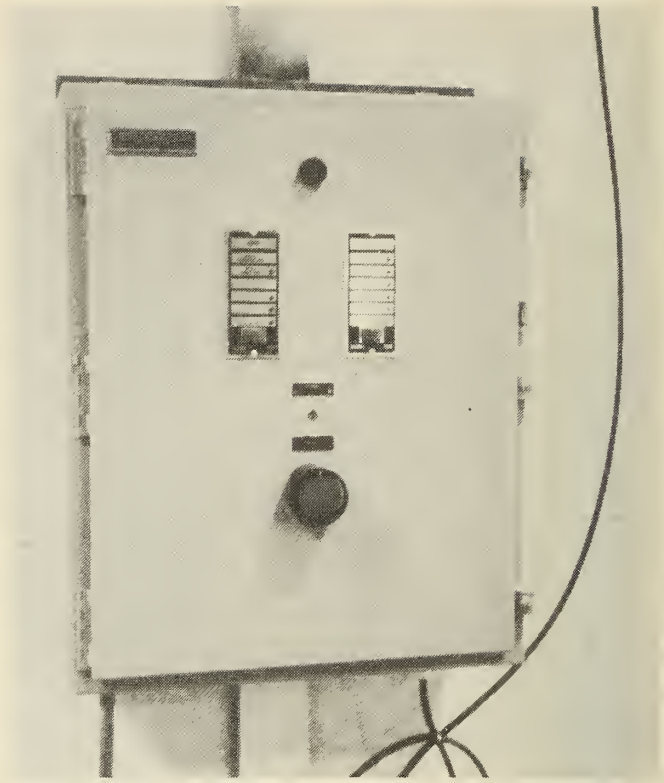

FIGURE 36. - Master panel installed in hoist room.

For the first-shift test, the elapsed times from actuation to detection ranged from 2 to 23 min on both the 1-4 and 1-5 levels (figs. 39-40). The maximum time was recorded at a location 3,400 ft from the remote vent shaft injection point on the 1-4 level. All recorded times compared closely to those recorded during the tests of the first-generation injector.

During the second-shift tests, elapsed times ranged from 1 to 30 min on both the 1-4 and 1-5 levels (figs. 40-41). Again, the maximum time was recorded at a location on the 1-4 level, 3,400 ft from the remote vent shaft injection point.

Mine management was pleased with the improved injector design and the new refilling system. Other significant improvements over the original design were one-valve actuation, the clear bowl on the ventilation-air injectors, and a new orifice plug for easier orifice removal. Based on the success of the laboratory and field testing of this system, a production version is now being commercially marketed. The injector is available for about $1,300, and a THT refill kit is available for about $100.

SUMMARY AND CONCLUSIONS

An improved stench warning system for underground noncoal mines has been developed and succesfully in-mine tested. The system utilizes a superior stench agent (THT) and employs an injector that dispenses a controlled volume of

FIGURE 37. - Remote-control telemetry system installed on leg of emergency-escape-hoist headframe at remote venthole.

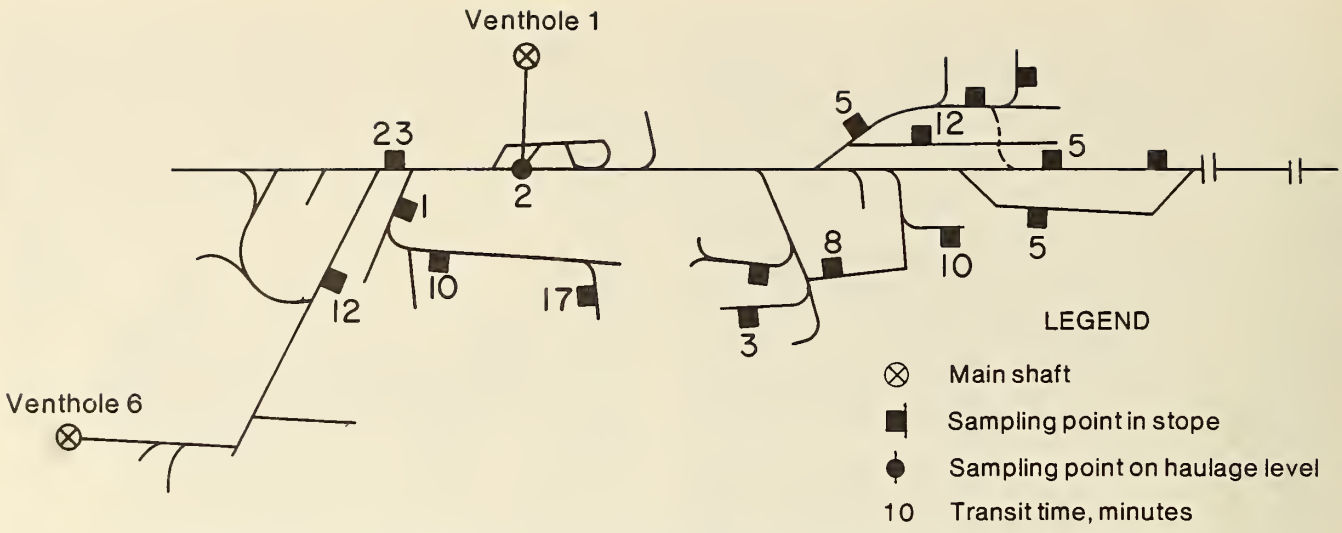

FIGURE 38. - Stench test results, second-generation system, first shift, 1-4 level.

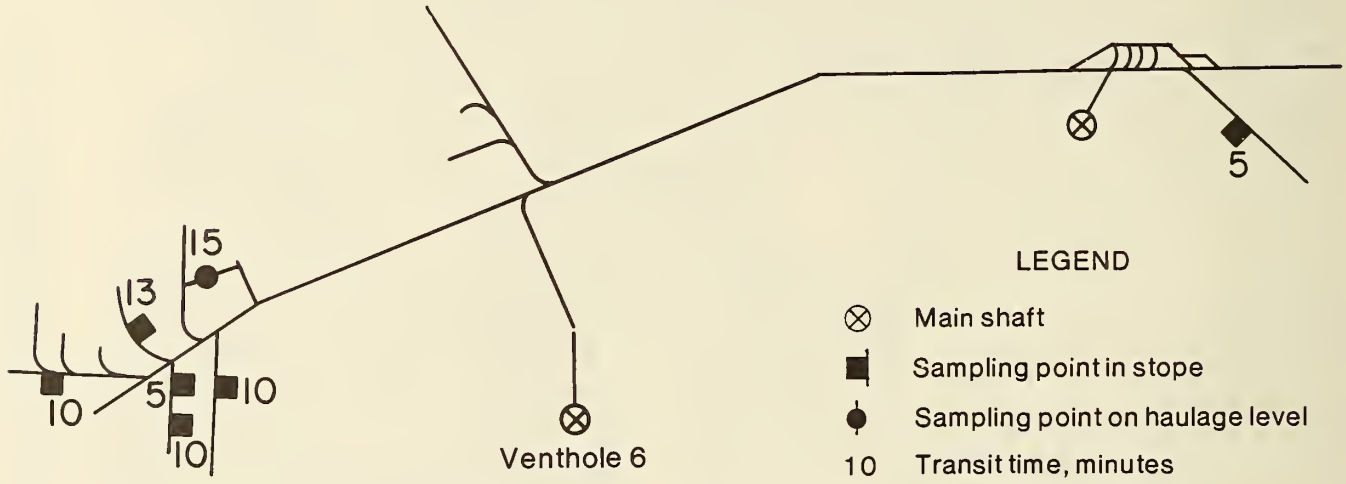

FIGURE 39. - Stench test results, second-generation system, first shift, 1-5 level.

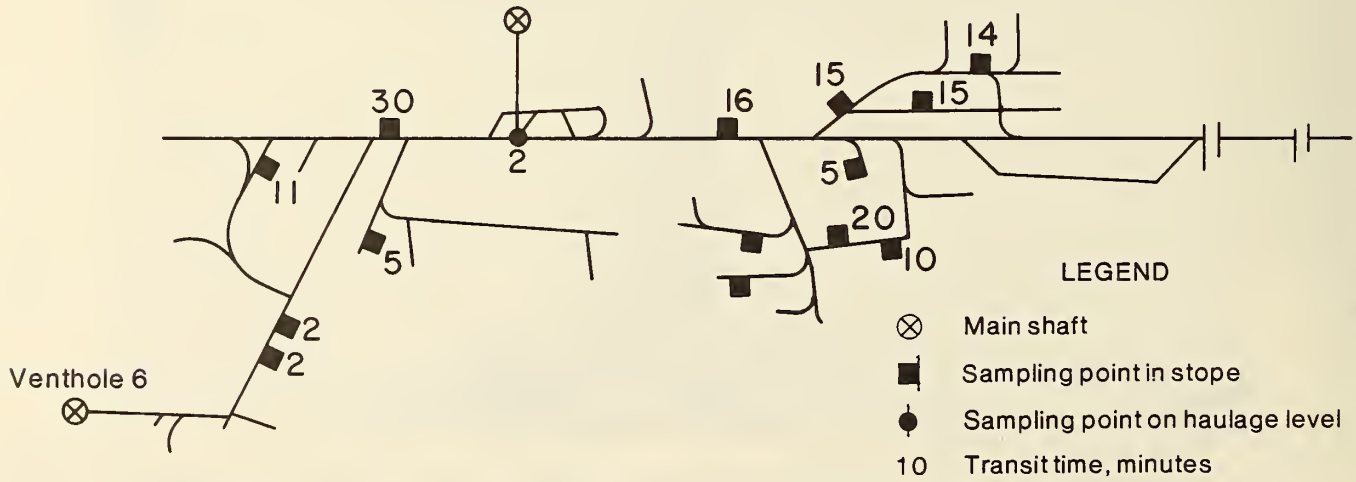

FIGURE 40. - Stench test results, second-generation system, second shift, 1-4 level.

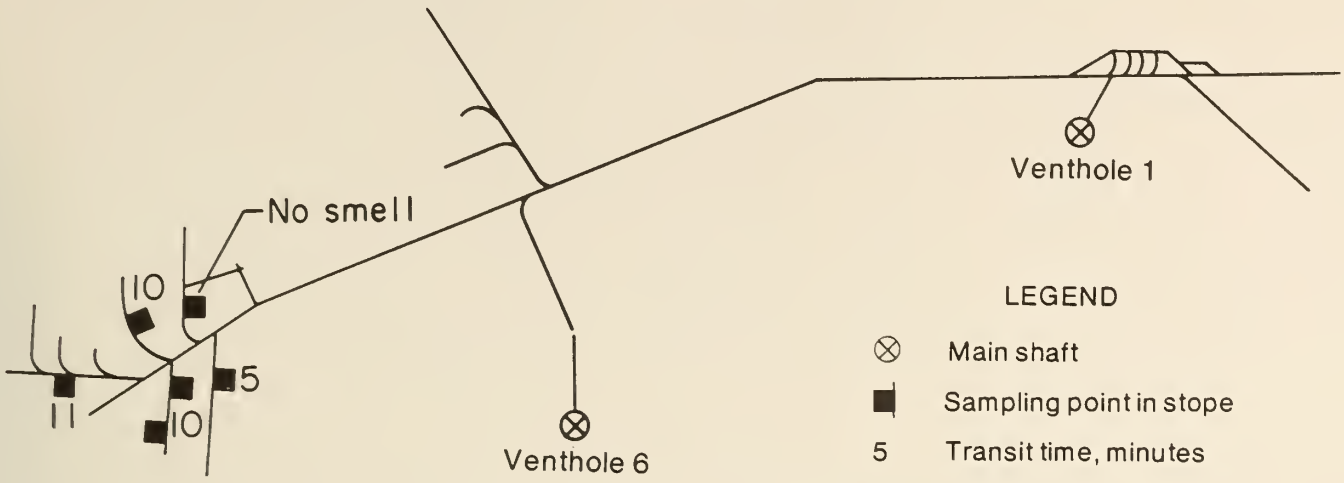

FIGURE 41. - Stench test results, second-generation system, second shift, 1-5 level.

stench fluid into either compressed or ventilation air. The system is simple, easy to use, requires little maintenance, is easy to recharge, and is designed for high reliability. It can be remotely operated by either wireless or hard-wired means. The system is commercially available for about $1,300 per injector.

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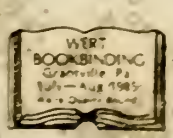

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